On the Side-Channel Resistance of UOV

Survey of Physical Attacks and Recent Developments

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Outline

1. UOV from Two Perspectives
2. Fault Attacks
   - Skip Random Sampling of Vinegar Variables [SK20]
   - Bit-Flip in Central Map [FKN+22]
3. Side Channel Attacks
   - Horizontal SCA on Linear Transformation [PSK+18]
   - Template Attack on Evaluation of Vinegar Variables [ACK+23]
4. Takeaways

UOV from Two Perspectives

UOV - a Remarkable Candidate

UOV stands out, since

- it is a comparably old scheme with 25 years of cryptanalysis
- many current (and past) multivariate signature schemes are modifications of it

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- 'e.g., **UOV**' ✓

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Comparison with Dilithium

Oil and Vinegar: Modern Parameters and Implementations[2]

Key sizes and performance data

Signature Scheme	public key	secret key (Bytes)	signature	KeyGen	Sign (Cycles)	Verify
ov-Ip	278 432	237 912	128	2 903 434	105 324	90 336
ov-Ip-pk**c**	43 576	237 912	128	2 858 724	105 324	224 006
ov-Ip-pk**c**-sk**c**	43 576	64	128	2 848 774	1 876 442	224 006
Dilithium2	1 312	2 544	2 420	124 031	333 013	118 412

[2] Beullens, W., Chen, M. S., Hung, S. H., Kannwischer, M. J., Peng, B. Y., Shih, C. J., and Yang, B. Y. (2023). Oil and Vinegar: Modern Parameters and Implementations. IACR TCHES, 321-365.

Multivariate Cryptography

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- **Verify** if $\mathcal{P}(\boldsymbol{s}) = \boldsymbol{t}$ really holds

Two Descriptions of UOV in the Literature (1/2)

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- Fix and insert vinegar variables $\tilde{v}_i$ to get m linear equations in m oil variables

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- Visualization of signing $\mathbf{t}$

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- T has block matrix structure $T = \begin{pmatrix} I_v & T_1 \\ 0 & I_m \end{pmatrix}$

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  $\rightarrow$ Solving $\mathcal{P}'(\boldsymbol{v}, \boldsymbol{o}) = \mathbf{t} - \mathcal{P}(\boldsymbol{v})$ means solving a system with m variables in m equations
- The vector $\boldsymbol{s} = \boldsymbol{v} + \boldsymbol{o}$ forms a valid signature

Fault Attacks

Skip Random Sampling of Vinegar Variables

Main idea

- Skip the random sampling of vinegar values (already discussed in [HTS11][3] and [KL19][4])

$$\mathbf{t} \xrightarrow{\quad \mathcal{F}^{-1} \quad} \begin{pmatrix} \mathbf{v} \\ \mathbf{y} \end{pmatrix} \xrightarrow{\quad T^{-1} \quad} \begin{pmatrix} \mathbf{s}_1 \\ \mathbf{s}_2 \end{pmatrix} = \begin{pmatrix} \mathbf{v} + T_1 \cdot \mathbf{y} \\ \mathbf{y} \end{pmatrix}$$

[3] Hashimoto, Y., Takagi, T., and Sakurai, K.: General Fault Attacks on Multivariate Public Key Cryptosystems. PQCrypto 2011

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- Solution to $\mathcal{F}^{-1}$ are the randomly generated vinegar values $\mathbf{v} = \left(v_1, \ldots, v_{n-m}\right)^\top$ and the computed oil variables $\mathbf{y} = \left(y_1, \ldots, y_m\right)^\top$

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- We have $\begin{pmatrix} \mathbf{s}_1^{(i)} \\ \mathbf{s}_2^{(i)} \end{pmatrix} - \begin{pmatrix} \mathbf{s}_1 \\ \mathbf{s}_2 \end{pmatrix} = \begin{pmatrix} T_1 \cdot (\mathbf{y}^{(i)} - \mathbf{y}) \\ (\mathbf{y}^{(i)} - \mathbf{y}) \end{pmatrix}$

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- Repeat m times to solve for T_1 (requires m faulted signatures)

Reduce Number of Needed Faulted Signatures

In fact, one can do even better

- The vector $\begin{pmatrix} \mathbf{s}_1^{(i)} \\ \mathbf{s}_2^{(i)} \end{pmatrix} - \begin{pmatrix} \mathbf{s}_1 \\ \mathbf{s}_2 \end{pmatrix} = \begin{pmatrix} T_1 \cdot (\mathbf{y}^{(i)} - \mathbf{y}) \\ (\mathbf{y}^{(i)} - \mathbf{y}) \end{pmatrix}$ represents an oil vector, i.e.

$$\mathcal{P}\begin{pmatrix} T_1 \cdot (\mathbf{y}^{(i)} - \mathbf{y}) \\ (\mathbf{y}^{(i)} - \mathbf{y}) \end{pmatrix} = \mathcal{F}\begin{pmatrix} I_v & T_1 \\ 0 & I_m \end{pmatrix}\begin{pmatrix} T_1 \cdot (\mathbf{y}^{(i)} - \mathbf{y}) \\ (\mathbf{y}^{(i)} - \mathbf{y}) \end{pmatrix} = \mathcal{F}\begin{pmatrix} \mathbf{0} \\ (\mathbf{y}^{(i)} - \mathbf{y}) \end{pmatrix} = \mathbf{0}$$

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$$\mathcal{P} \begin{pmatrix} T_1 \cdot (\mathbf{y}^{(i)} - \mathbf{y}) \\ (\mathbf{y}^{(i)} - \mathbf{y}) \end{pmatrix} = \mathcal{F} \begin{pmatrix} I_v & T_1 \\ 0 & I_m \end{pmatrix} \begin{pmatrix} T_1 \cdot (\mathbf{y}^{(i)} - \mathbf{y}) \\ (\mathbf{y}^{(i)} - \mathbf{y}) \end{pmatrix} = \mathcal{F} \begin{pmatrix} \mathbf{0} \\ (\mathbf{y}^{(i)} - \mathbf{y}) \end{pmatrix} = \mathbf{0}$$

- This is easy to recognize in the oil space description, since

$$\mathbf{s}^{(i)} - \mathbf{s} = (\mathbf{v} + \mathbf{o}^{(i)}) - (\mathbf{v} + \mathbf{o}) = \mathbf{o}^{(i)} - \mathbf{o} \in O$$

Reduce Number of Needed Faulted Signatures

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- One oil vector enables key recovery in polynomial time $\rightarrow$ next slide

Algebraic Attack

Knowledge of an oil vector dramatically simplifies algebraic key recovery attacks

- For two oil vectors $\mathbf{o}_1, \mathbf{o}_2$ it holds

$$\mathcal{P}'(\mathbf{o}_1, \mathbf{o}_2) = \mathcal{P}(\mathbf{o}_1 + \mathbf{o}_2) - \mathcal{P}(\mathbf{o}_1) - \mathcal{P}(\mathbf{o}_2) = \mathbf{0} \in \mathbb{F}_q^m$$

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Details can be found in [ACK+23] [6]

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[6] Aulbach, T., Campos, F., Krämer, J., Samardjiska, S., and Stöttinger, M.: Separating Oil and Vinegar with a Single Trace: Side-Channel Assisted Kipnis-Shamir Attack on UOV. IACR TCHES 2023

Summary of the Fault Attack [SK20]

Summary

- **Instruction skip** to reuse the vinegar variables
- **Number** of needed **faulted signatures** is reduced from m to now only **1**
- Distinguish between reuse and zero setting (analyzed in [SK20][7] and [KKT22][8])

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- Store old vinegar variables and only output signature if there are no large overlaps

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Future work

- Execute instruction skip on a target device
- Apply to various modifications of UOV

Bit-Flip in Central Map

Fault model

- Introduce a fault that changes one coefficient ${\alpha'}_{i,j}^{(k)}$ in the central map $\mathcal{F}$ (already discussed in [HTS11] and [KL19])
- Faulted coefficient is randomly chosen and attacker does not know its location

$$F'^{(k)} = \begin{pmatrix} \alpha_{1,1}^{(k)} & \dots & \alpha_{1,v}^{(k)} & \alpha_{1,v+1}^{(k)} & \dots & \alpha_{1,n}^{(k)} \\ 0 & \ddots & \vdots & \vdots & {\alpha'}_{i,j}^{(k)} & \vdots \\ 0 & 0 & \alpha_{v,v}^{(k)} & \alpha_{v,v+1}^{(k)} & \dots & \alpha_{v,n}^{(k)} \\ 0 & \dots & 0 & 0 & \dots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & 0 & \dots & 0 \end{pmatrix}$$

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$$
\begin{pmatrix} \tilde{v}_1 \\ \vdots \\ \tilde{v}_v \\ y_1 \\ \vdots \\ y_m \end{pmatrix}^{\top}
\begin{pmatrix}
\alpha_{1,1}^{(k)} & \dots & \alpha_{1,v}^{(k)} & \alpha_{1,v+1}^{(k)} & \dots & \alpha_{1,n}^{(k)} \\
0 & \ddots & \vdots & \vdots & {\alpha'}_{i,j}^{(k)} & \vdots \\
0 & 0 & \alpha_{v,v}^{(k)} & \alpha_{v,v+1}^{(k)} & \dots & \alpha_{v,n}^{(k)} \\
0 & \dots & 0 & 0 & \dots & 0 \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
0 & \dots & 0 & 0 & \dots & 0
\end{pmatrix}
\begin{pmatrix} \tilde{v}_1 \\ \vdots \\ \tilde{v}_v \\ y_1 \\ \vdots \\ y_m \end{pmatrix}
= l_1^{(k)} \cdot y_1 + \ldots + l_j^{(k)} \cdot y_j + \ldots + c^{(k)}
$$

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$$

- One coefficient in the k-th linear equation is altered

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Fault propagation

$$\mathbf{t} \xrightarrow{\mathcal{F}'^{-1}} \begin{pmatrix} \mathbf{v} \\ \mathbf{y} \end{pmatrix} \xrightarrow{T^{-1}} \begin{pmatrix} \mathbf{s}_1 \\ \mathbf{s}_2 \end{pmatrix} = \mathbf{s}'$$

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- This yields quadratic equations in the i-th and j-th row of T

Key Recovery

Iterate the following steps to achieve key recovery (Details in [FKN+22][10])

1. Employ signing oracle to get $N = n(n+1)/2$ message and faulted signature pairs
2. Obtain rows of the secret transformation T
3. Transform $\mathcal{P}$ to a smaller system by reducing the number of variables

[10] Furue, H., Kiyomura, Y., Nagasawa, T., and Takagi, T.: A New Fault Attack on UOV Multivariate Signature Scheme. PQCrypto 2022

Summary of the Fault Attack [FKN+22]

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- Randomization fault
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Future work

- Find a way to physically cause the randomization in exactly one entry
- Transfer the attack to implementation with compressed keys, where the central map is not stored

A Fault Attack on LUOV [MIS20]

QuantumHammer: A Practical Hybrid Attack on the LUOV Signature Scheme[11]

[11] Mus, K., Islam, S., and Sunar, B. QuantumHammer: A Practical Hybrid Attack on the LUOV Signature Scheme. ACM SIGSAC Conference on Computer and Communications Security 2020

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- Might be transferred to UOV

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Side Channel Attacks

Horizontal SCA on Linear Transformation T

Main idea[12]

$$\mathrm{t} \xrightarrow{\quad\mathcal{F}^{-1}\quad} \begin{pmatrix} \mathrm{v} \\ \mathrm{y} \end{pmatrix} \xrightarrow{\quad T^{-1}\quad} \begin{pmatrix} \mathrm{s}_1 \\ \mathrm{s}_2 \end{pmatrix} = \begin{pmatrix} \mathrm{v} + T_1 \cdot \mathrm{y} \\ \mathrm{y} \end{pmatrix}$$

- Perform power analysis of matrix-vector multiplication

$$\begin{pmatrix} I_v & T_1 \\ 0 & I_m \end{pmatrix} \cdot \begin{pmatrix} \mathrm{v} \\ \mathrm{y} \end{pmatrix} = \begin{pmatrix} \mathrm{v} + T_1 \cdot \mathrm{y} \\ \mathrm{y} \end{pmatrix}$$

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- Either obtain all entries of T by SCA or identify certain rows and reduce the system $\mathcal{P}$ as shown in previous fault attack

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Matrix-Vector Multiplication

The vulnerable function in more detail

$$\begin{pmatrix} I & T_1 \\ 0 & I \end{pmatrix} \cdot \begin{pmatrix} \mathbf{v} \\ \mathbf{y} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & t_{1,4} & t_{1,5} \\ 0 & 1 & 0 & t_{2,4} & t_{2,5} \\ 0 & 0 & 1 & t_{3,4} & t_{3,5} \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ y_1 \\ y_2 \end{pmatrix} + \begin{pmatrix} t_{1,4} \cdot y_1 + t_{1,5} \cdot y_2 \\ t_{2,4} \cdot y_1 + t_{2,5} \cdot y_2 \\ t_{3,4} \cdot y_1 + t_{3,5} \cdot y_2 \\ 0 \\ 0 \end{pmatrix}$$

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1. Guess intermediate values and map hypothetical value to hypothetical power consumption of the function under investigation

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2. Measure the power consumption of the target device

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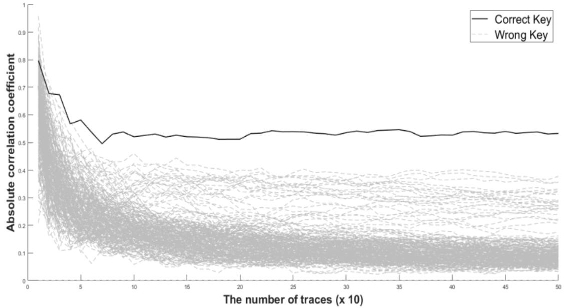
1. Guess intermediate values and map hypothetical value to hypothetical power consumption of the function under investigation
2. Measure the power consumption of the target device
3. Perform statistical comparison between hypothetical power consumption and measured power traces

Compute Correlation with Hypothetical Values

Example with clear separation between correct key elements and wrong key element

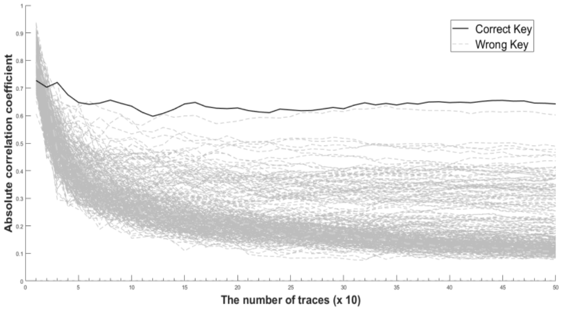


(a) Maximum correlation coefficients according to increased number of traces for $\widetilde{t}_{45}$

Correlation coefficients for all possible field elements and the entry t_{45} [PSK+18]

Compute Correlation with Hypothetical Values

Example with two possible candidate for the correct key element



(b) Maximum correlation coefficients according to increased number of traces for $\widetilde{t}_{46}$

Correlation coefficients for all possible field elements and the entry t_{46} [PSK+18]

Summary of the Horizontal SCA

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- Correlation power analysis on field multiplication
- Around 30 – 100 power traces are needed to recover field elements

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- Target board is an 8-bit Atmel XMEGA128 (might be more difficult on 32-bit devices)
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Future work

- Analyze efficiency impact of countermeasures
- Transfer the attack to modern and optimized implementations

Main idea[13]

- Measure power consumption of $\mathcal{P}(\mathbf{v})$

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Attack Insertion of Vinegar Values in Public Key Map

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- This operation boils down to computing $\mathbf{v}^\top P^{(k)}\mathbf{v}$ for m known matrices $P^{(k)}$

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- Consider the matrix-vector multiplication

$$P^{(k)} \cdot \mathbf{v} = \begin{pmatrix} p_{1,1}^{(k)} & p_{1,2}^{(k)} & \cdots & p_{1,n}^{(k)} \\ & p_{2,2}^{(k)} & \cdots & p_{2,n}^{(k)} \\ & & \ddots & \vdots \\ & & & p_{n,n}^{(k)} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{pmatrix} \text{ for } k \in \{1, \ldots, m\}$$

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- Secret $\mathbf{v}$ is multiplied with a considerable amount of known values

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- Create a template by tracing the power consumption of

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- For each field element, we need to run and trace the matrix-vector multiplication only once $\rightarrow$ in total $q = 256$ profiling traces
- Can be collected on another device (subtract some mean to erase the 'footprint' of the device)

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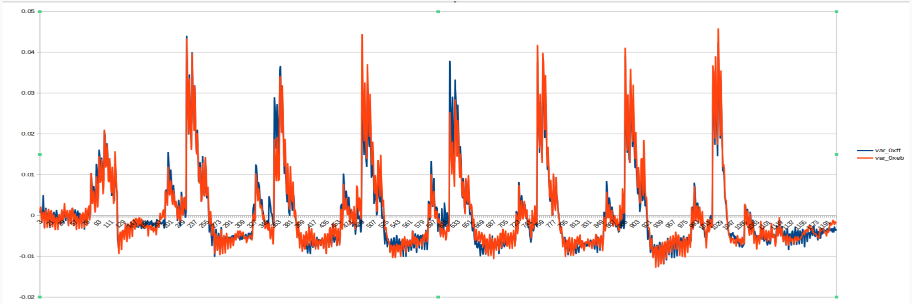
- Consider the following example



Compare power traces with $v_i = 0xFF$ vs $v_i = 0xEB$

Compute Correlation

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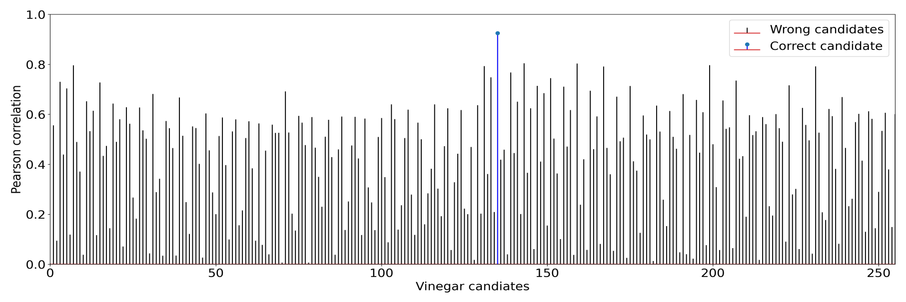
- Compute correlation to templates for each entry of $\boldsymbol{v}$



Correlation of the target trace with each of the 256 reference traces

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- Very high success probability ($\approx 97\%$) for all vinegar variables
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Future work

- Analyze efficiency impact of countermeasures
- Apply the attack to M4 implementations or using a different setup

Takeaways

The End

Takeaways

- Vinegar vectors and oil vectors should be equally secured
- With one of those, the secret key can be recovered in polynomial time
- Some physical attacks are still in a theoretical or simulated state
- Efficiency impact of countermeasures should be analyzed

Questions?
Contact: thomas.aulbach@ur.de

Aulbach, Campos, Krämer, Samardjiska, Stöttinger:
Separating Oil and Vinegar with a Single Trace
https://ia.cr/2023/335

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