Side-Channel Analysis of MAC-Keccak Hardware Implementations

Northeastern University Energy-Efficient and Secure Systems Lab
Outline

- Details of Keccak
- Previous attacks on Keccak
- Side-channel attacks on $R_1$
- Conclusion
Details of Keccak (1)

- Selected as the winner of the [NIST hash function competition](#) on October 2, 2012
- Draft FIPS PUB 202, May 2014
  - SHA3-224, SHA3-256, SHA3-384, SHA3-512, SHAKE128, SHAKE256
  - Internal state size: 1600 (5×5×64)

- In this paper:
  - 320 key bits, fill the first plane
Details of Keccak (2)

\[ R_{i+1} = \iota \circ \chi \circ \pi \circ \rho \circ \theta(R_i), \quad i \in \{0, 1 \ldots 23\} \]
Details of Keccak (3)

- \( \theta \) is a linear operation which involves 11 input bits and outputs a single bit.

\[
S'(x,y,z) = S(x,y,z) \oplus (\bigoplus_{i=0}^{4} S(x-1,i,z)) \oplus (\bigoplus_{i=0}^{4} S(x+1,i,z-1)).
\]
Details of Keccak (4)

- $\rho$ is the permutation over the bits along the z-axis.
- $\pi$ changes $x$ and $y$ of the bits
Details of Keccak (5)

- $\chi$ is the only non-linear step
- $\nu$ is addition with a constant number
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Side-channel attacks on $\theta$ (1)

- Previous papers focus on $\theta$
  - The first step of Keccak
  - Intermediate variables are stored in registers for software implementations
  - Hardware implementations also have leakage of $\theta$ because of Keccak properties


P. Luo, Y. Fei, X. Fang, A. Ding, M. Leeser, and D. Kaeli. Power analysis attack on hardware implementation of MAC-keccak on FPGAs. In ReConFigurable Computing and FPGAs (ReConFig), 2014 International Conference on, pages 1-7, Dec 2014.
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Side-channel attacks on $R_1$ (1)

- Each $\chi_{out}$ bit involves 3 bits of $\pi_{out}$;
- Each $\pi_{out}$ bit involves 2 key bits.

Conclusion:
(1) One bit SNR is too low;
(2) One bits involves at least 6 key bits.
Side-channel attacks on $R_1$ (2)

$R_1([0:4], 4, 0)$

5 bits of each row operate on each other, thus 11 key bits in total. Attackable?
Side-channel attacks on $R_1$ (3)

Hamming distance:

$$HD(P([0:4],4,0), R_1([0:4],4,0))$$

$P([0:4],4,0)$ is known, how to get $R_1$:

- $R_1(0,4,0) \leftrightarrow \theta_{out}(2,0,2) \leftrightarrow P(2,0,2)$
- $R_1(1,4,0) \leftrightarrow \theta_{out}(3,1,9) \leftrightarrow P(3,1,9)$
- $R_1(2,4,0) \leftrightarrow \theta_{out}(4,2,25) \leftrightarrow P(4,2,25)$
- $R_1(3,4,0) \leftrightarrow \theta_{out}(0,3,23) \leftrightarrow P(0,3,23)$
- $R_1(4,4,0) \leftrightarrow \theta_{out}(1,4,62) \leftrightarrow P(1,4,62)$

$P(2,0,2)$ is also a key bit, thus 11 key bits
Side-channel attacks on $R_1(4)$

$\pi$ and $\rho$ only change the position of bits, the values are not changed.

- $R_1(0,4,0) \leftrightarrow \theta_{out}(2,0,2) \leftrightarrow P(2,0,2)$
- $R_1(1,4,0) \leftrightarrow \theta_{out}(3,1,9) \leftrightarrow P(3,1,9)$
- $R_1(2,4,0) \leftrightarrow \theta_{out}(4,2,25) \leftrightarrow P(4,2,25)$
- $R_1(3,4,0) \leftrightarrow \theta_{out}(0,3,23) \leftrightarrow P(0,3,23)$
- $R_1(4,4,0) \leftrightarrow \theta_{out}(1,4,62) \leftrightarrow P(1,4,62)$
Side-channel attacks on $R_1$ (5)

$R_1(0,4,0) \iff \theta_{out}(2,0,2) \iff P(2,0,2)$

$R_1(1,4,0) \iff \theta_{out}(3,1,9) \iff P(3,1,9)$

$R_1(2,4,0) \iff \theta_{out}(4,2,25) \iff P(4,2,25)$

$R_1(3,4,0) \iff \theta_{out}(0,3,23) \iff P(0,3,23)$

$R_1(4,4,0) \iff \theta_{out}(1,4,62) \iff P(1,4,62)$

What can we recover:

$k g_1 = P(2,0,2) \oplus P(1,0,2) \oplus P(3,0,1)$

$k g_2 = P(2,0,9) \oplus P(4,0,8)$

$k g_3 = P(3,0,25) \oplus P(0,0,24)$

$k g_4 = P(4,0,23) \oplus P(1,0,22)$

$k g_5 = P(1,0,62) \oplus P(2,0,61)$
Side-channel attacks on $R_1$ (6)

(a) Key guess for $R_1([0:4],4,0)$
Side-channel attacks on $R_1$ (7)
Side-channel attacks on $R_1$ (8)

$$KG_1 = \{ S(x -1,0,z) \oplus S(x,0,z) \oplus S(x +1,0,z-1) \}$$

$$KG_2 = \{ S(x -1,0,z) \oplus S(x +1,0,z-1) \}$$

$x \in \{0,1\ldots\}$, $z \in \{0,1\ldots63\}$.

- Combine 2-bit XORs and 3-bit XORs to recover key bits
- There are 320 identical 2-bit XORs and 3-bit XORs
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- The first round output of Keccak can be attacked
- Attacking methods are different for software/hardware implementations
- Countermeasures should be added
Thanks!

http://tescase.coe.neu.edu/