On the Power of Power Analysis in the Real World: A Complete Break of the KeeLoq Code Hopping Scheme

CRYPTO 2008

August 17-21, 2008

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Acknowledgement

We would like to thank Andrey Bogdanov for bringing KeeLoq to our attention and for many helpful discussions.

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2. KeeLoq block cipher
3. Side-channel attacking KeeLoq
4. Results

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History of Side-Channel Attacks (1-slide version)

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- Existence of side-channels for crypto devices known for several decades, (e.g., „Tempest“)
- Few concrete results / poor understanding prior to 1996 (at least outside intelligence community)
- 2nd half of 1990s: golden years of SCA
  - RSA CRT attack, 1996
  - Timing attacks, 1996
  - SPA, DPA, 1998
- Since 1999: 100‘s of SCA research papers, e.g. in CHES
- But: very few (if any) documented real-world attacks to date

Modern Keyless Entry Systems: Hopping Code (aka Rolling Code)

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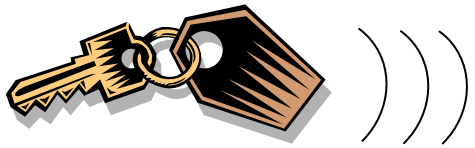
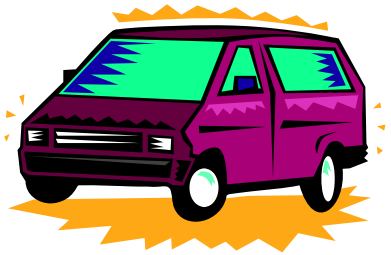
advanced theft control: rolling code



code = $e_k(n_i)$



$e_k()$ is often a block cipher

rolling code (or hopping code) protects against replay attacks:

1. code = $e_k(n)$
2. code = $e_k(n+1)$
3. code = $e_k(n+2)$

....

Alternatively, challenge-response protocols can be used
(but require bidirectional channel)

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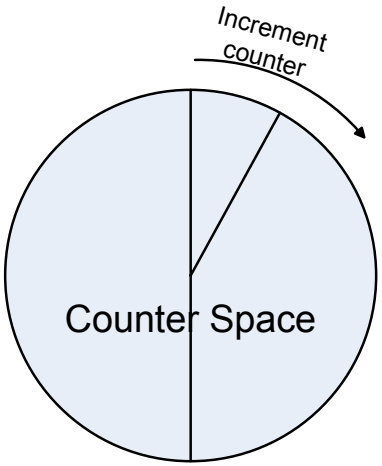
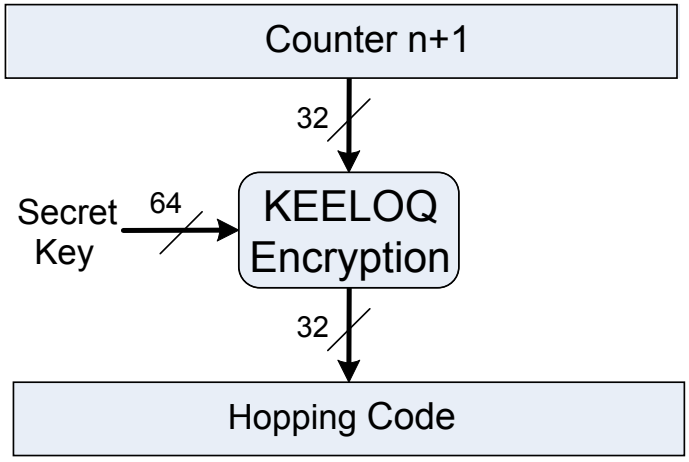
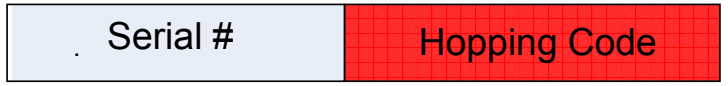
KeeLoq Rolling Code Scheme





Receiver decrypts & checks validity of counter value



KeeLoq Key Management

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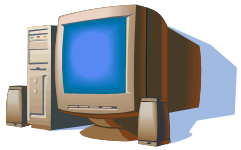
OEM gets *Manufacturer Key* k_M assigned (burned in all its receivers)

1) **Creation of new remote (in secure environment)**



k_M

#ser

k_{dev} = KeeLoq(#ser, k_M)

Key derivation

2) **Key Learning Phase of receiver** (keys are never sent in clear)

#ser

k_M

1. computes k_{dev} = KeeLoq(#ser, k_M)
2. stores (#ser , k_{dev})

Remark: simple XOR-based key derivation also possible

KeeLoq Applications

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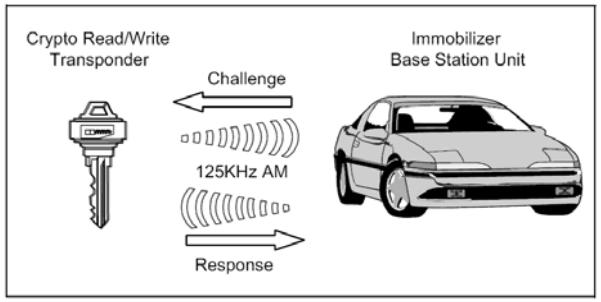
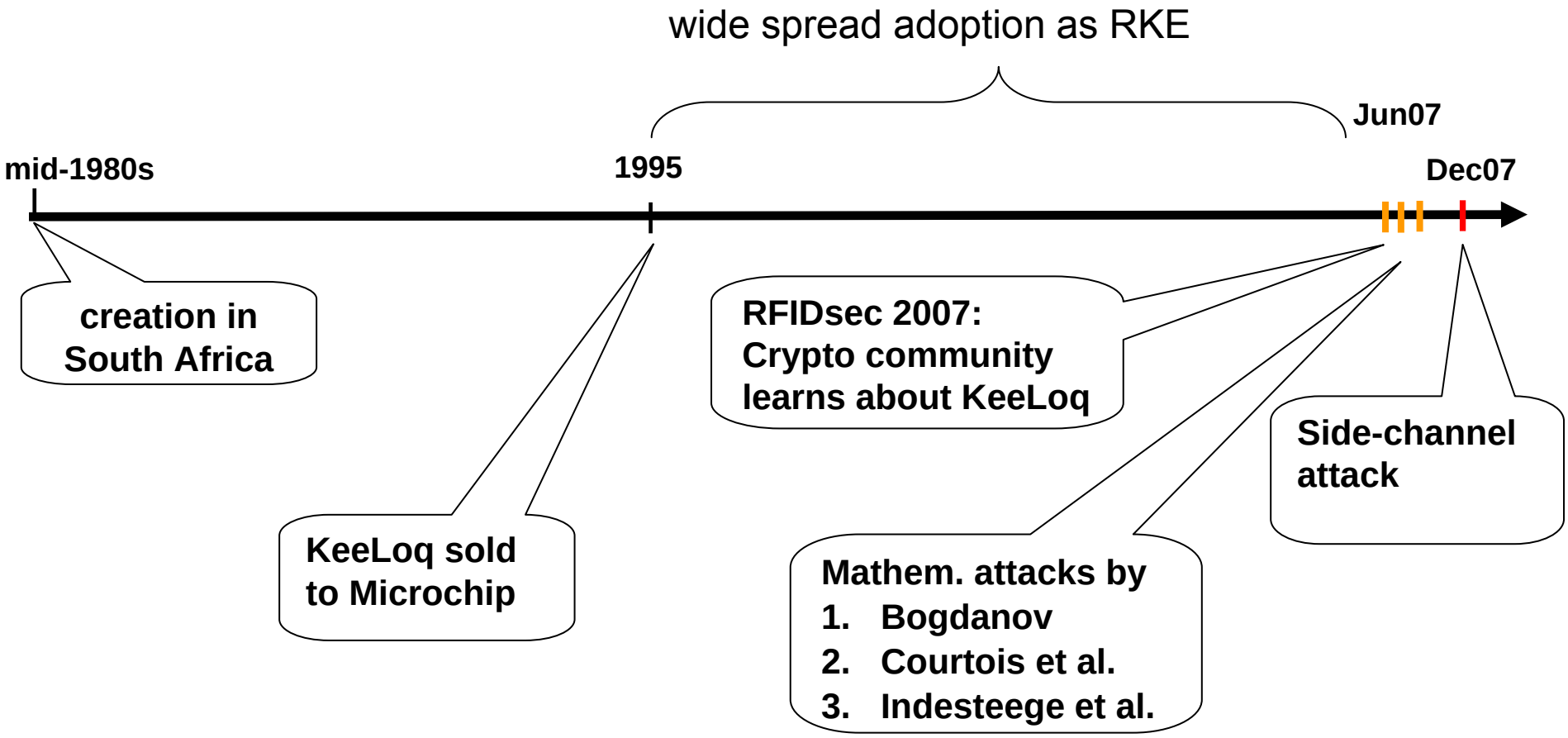
HCS410 IMMOBILIZER TRANSPONDER



- automotive and building access authentication
- KeeLoq implemented in hardware (transmitter) or software (receiver)
- can be used as rolling code or challenge-response
- very widely used for **garage doors** in US and Europe
- Wikipedia (?) Car door opening: Chrysler, Daewoo, Fiat, GM, Honda, Toyota, Volvo, Jaguar, ...

Q: How secure is KeeLoq?

Rise and Fall of KeeLoq



Mathematical Attacks: Recovery of Manufacturer Key

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	XOR Key Derivation	KeeLoq Key Derivation
Challenge-Response	Y	N
Rolling Code	N	N

- Mathematical attack (sliding attack) is cryptanalytically very impressive!
  Device Key is recovered from 2^{16} known plain/ciphertext pairs
- Problem: Rolling code mode does not provide plaintext!

- **Q: How dangerous are physical attacks?**

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Side Channel Analysis

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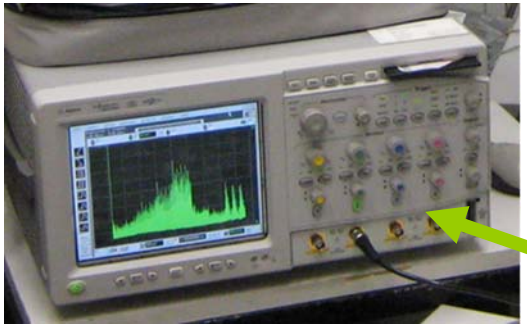

secret key of remote control (HCS XXX Chip) !

Performing the Side Channel Attack

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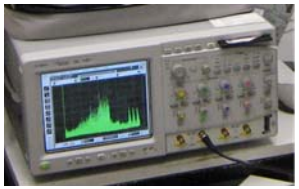


Analyze cipher

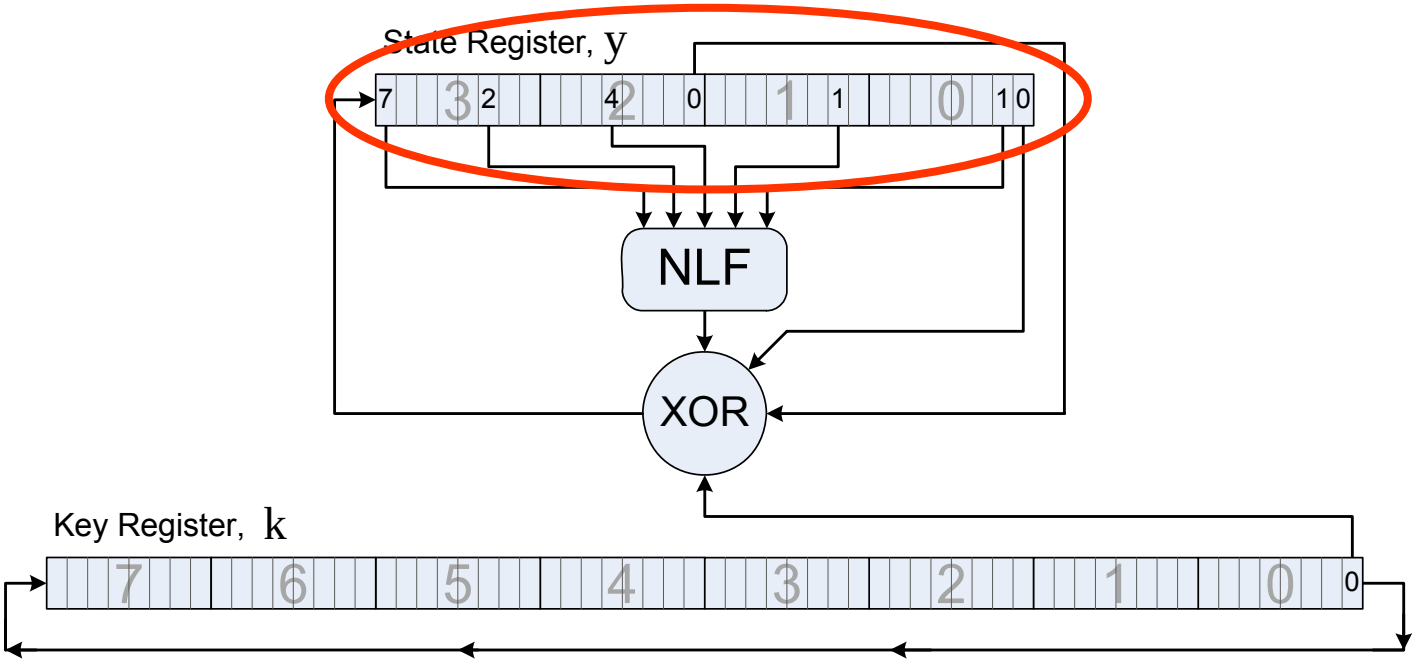
Measurements

Post Processing

Key Recovery

1. Find a suited predictable intermediate value in the cipher
2. Perform power measurements
3. Post-process acquired data
4. Perform the attack to recover the key

KeeLoq – The Algorithm



- 64 bit key, 32 bit block length
- NLFSR comprising a 5x1 non-linear function
- Simple key schedule: key is rotated
- 528 round, each round one key bit is read
- → Lightweight cipher – cheap and efficient in hardware

Power Consumption:

- logic is negligible
- depends on number of toggling 0s and 1s of the **registers**
- power consumption of Key Register is constant (fixed Hamming distance)

→ **Changes** in power consumption is related to state which leaks key information

Performing the Side-Channel Attack

1. Find a suited predictable intermediate value in the cipher
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Measuring the Power Consumption

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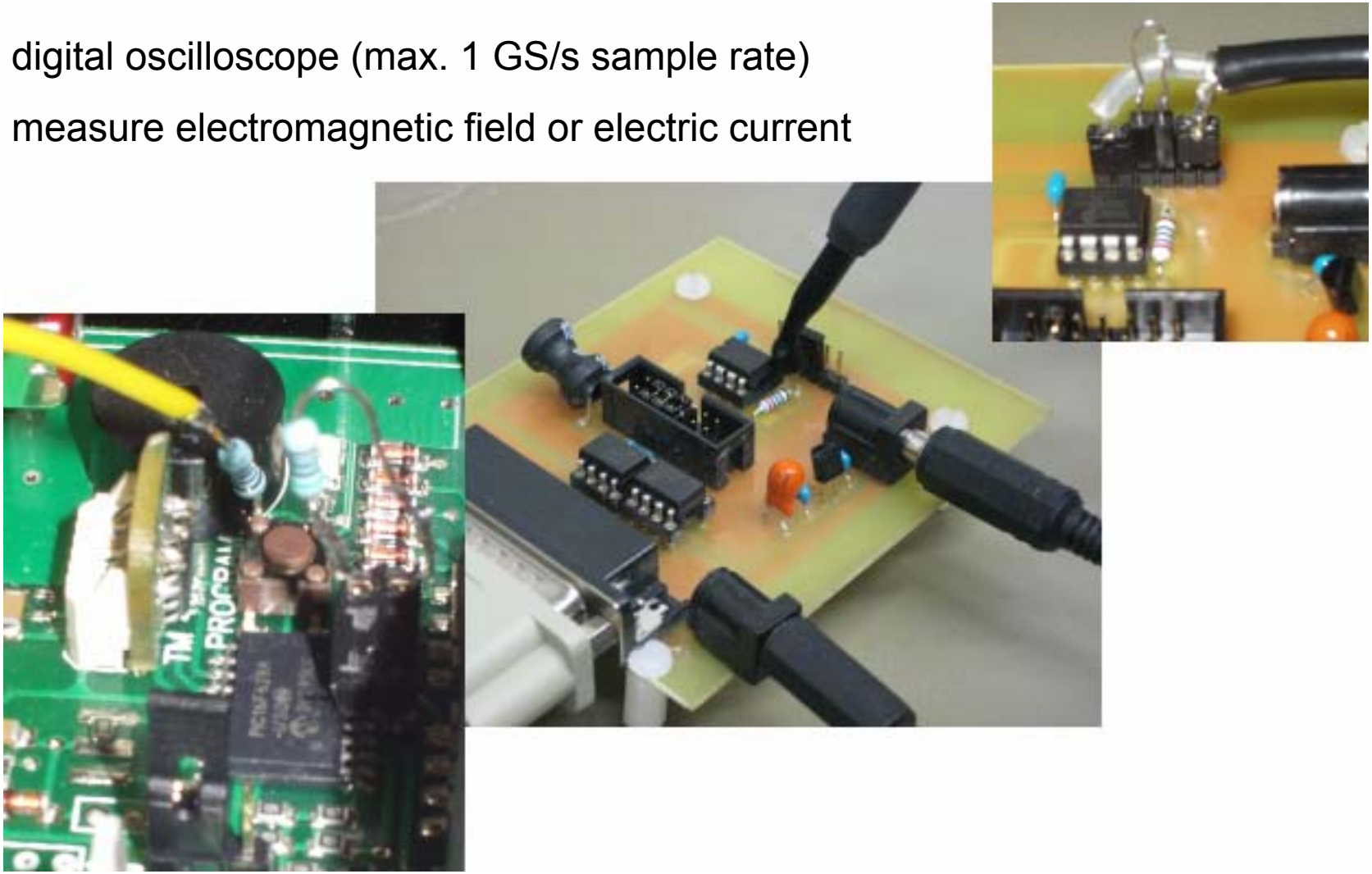
- digital oscilloscope (max. 1 GS/s sample rate)
- measure electromagnetic field or electric current



Identifying the KEELOQ - Encryption

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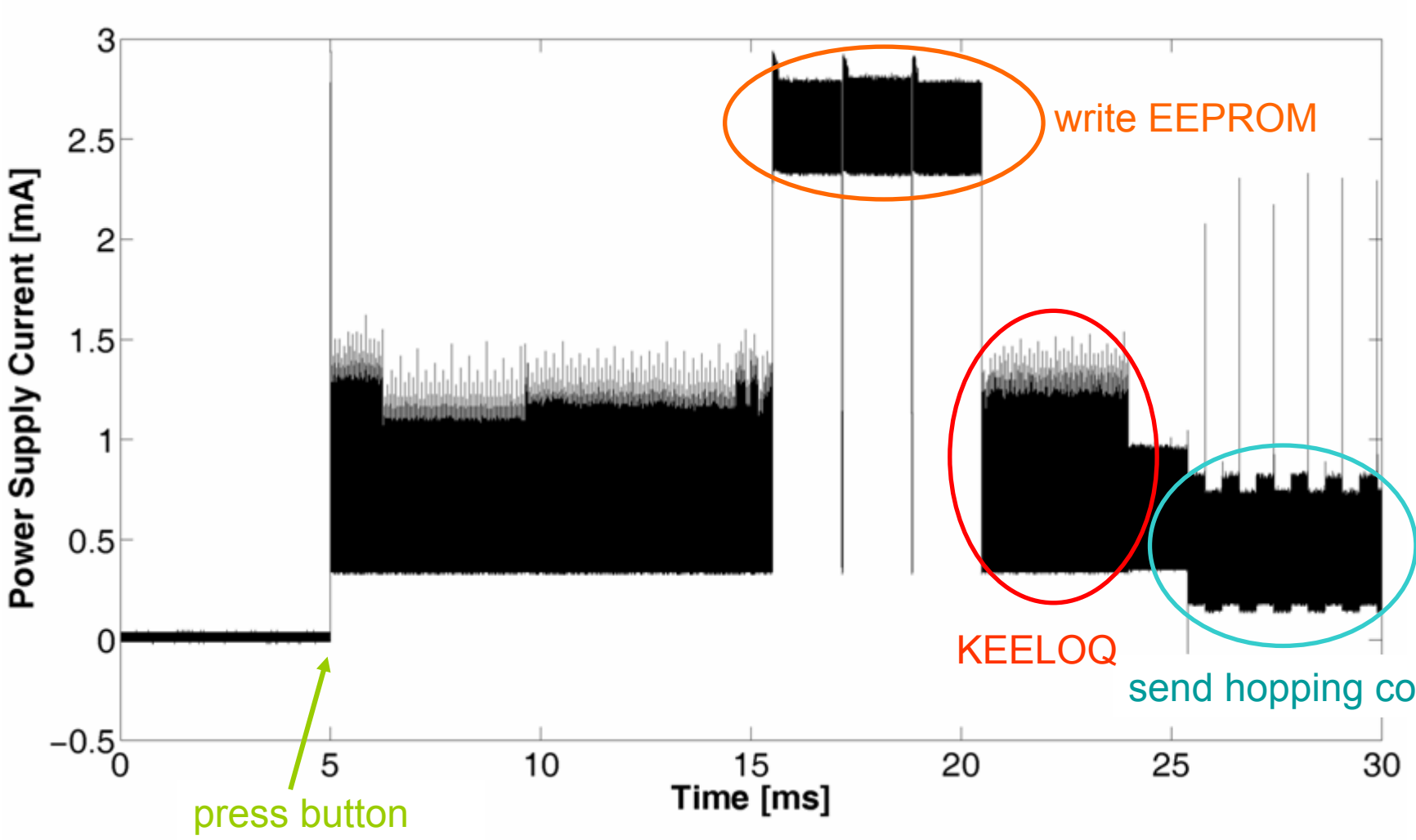

Performing the Side-Channel Attack

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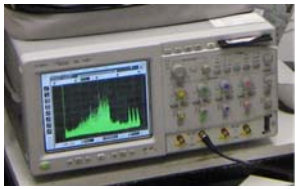

Analyze cipher

Measurements

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Performing the Side-Channel Attack
Key Recovery

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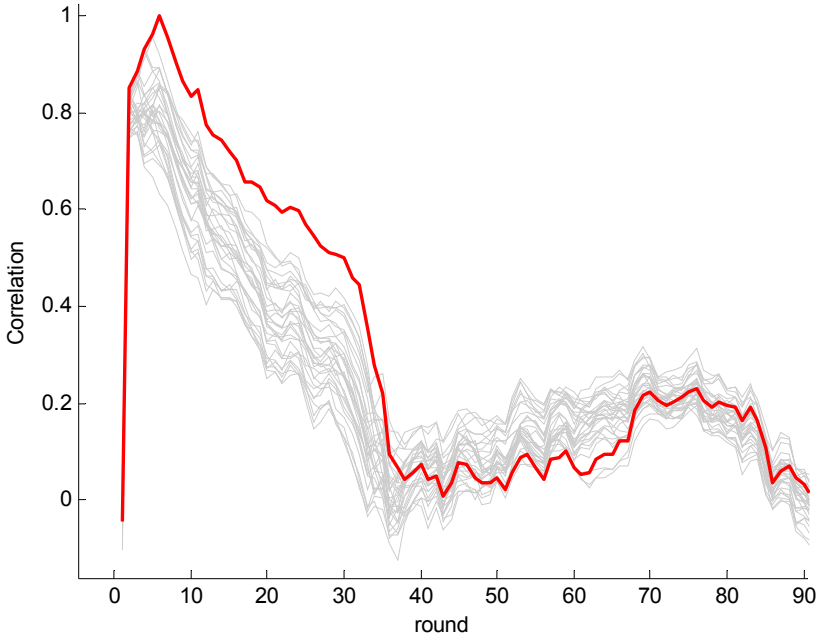
- Correlate measured power consumption to predicted key-dependent value y = f(x,k)
- Divide and conquer approach
- Much off-line number crunching



$$r\left(I_i(t), D(X_i, K_h)\right) = \frac{\sum_{i=1}^{M} I_i(t) \cdot D(X_i, K_h)}{\sqrt{\sum_{i=1}^{M} \left(I_i(t) - \overline{I_i(t)}\right)^2 \cdot \sum_{i=1}^{M} \left(D(X_i, K_h) - \overline{D(X_i, K_h)}\right)^2}} - \frac{\frac{1}{M} \cdot \sum_{i=1}^{M} I_i(t) \cdot \sum_{i=1}^{M} D(X_i, K_h)}{\sqrt{\sum_{i=1}^{M} \left(I_i(t) - \overline{I_i(t)}\right)^2 \cdot \sum_{i=1}^{M} \left(D(X_i, K_h) - \overline{D(X_i, K_h)}\right)^2}}$$

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Side Channel Attack on transmitters

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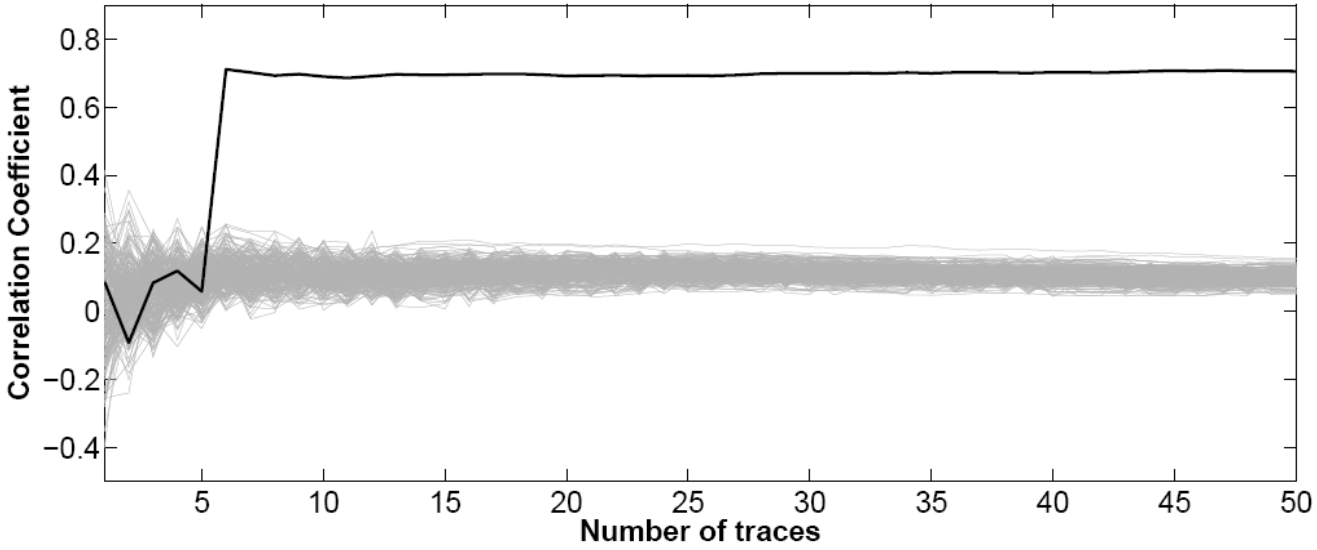
KeeLoq implemented in hardware

Total attack time (for known device family):
5-30 traces, ≈ minutes



Convergence of correlation coefficient

Rem: low cost equipment suffices (< $1000)

So what can we do now (1) ?

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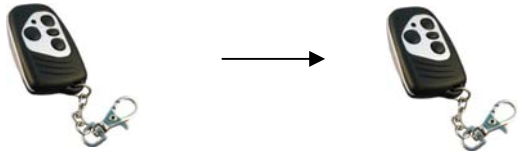
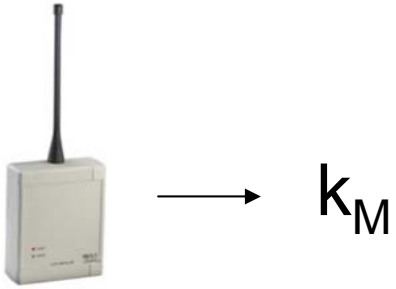
1. If we have access to a remote:



   Recover device key and clone the device

2. If we have access to a receiver:

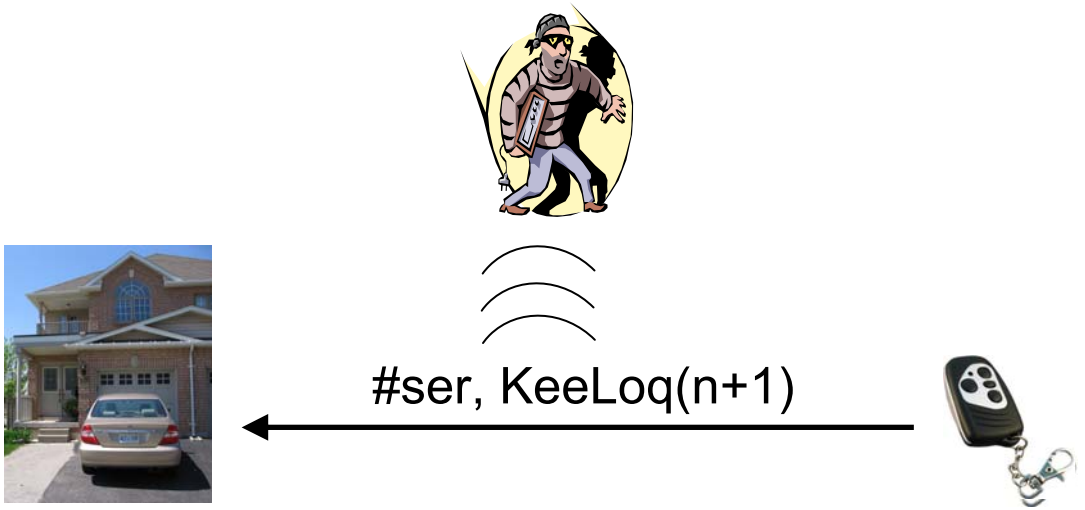


   Recover manufacturer key

So what can we do now (2) ?

After extracting of manufacturing key:

Remotely eavesdrop on 1-2 communications & clone key!



- works for all key derivation schemes
- might require a few hours of computation
  (Rem: not necessary for any system we‘ve analysed.)
- SCA attack is not specific to KeeLoq, e.g., unprotected AES is vulnerable too.

**! Side-channel step (recovery of manufacturer key, difficult)
can be outsourced to criminal cryptographers !**

Thanks for your attention!

more info: www.crypto.rub/keeloq

DOS - Denial Of Service

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• Receiver updates its internal counter according to the last received valid Rolling Code

• Generate valid Rolling Code with chosen counter value

• Counter of original remote control is in the block window → Door will not open.