On the Power of Power Analysis

A Complete Break of the Keyless Entry System *KeeLoq*

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Agenda

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- Remote Keyless Entry (RKE) Systems
- KeeLoq Block Cipher
- Side-Channel Attacking KeeLoq
- Results and Implications

How do Keyless Entry Systems work?

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early access controls: fixed code (“password”)

code

eavesdropper duplicates key (cloning)

but the industry learned…

Modern Keyless Entry Systems

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advanced theft control: rolling code

$code = e_k(n_i)$

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

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

....

$e_k()$ is often a block cipher

Alternative: Challenge-Response (aka IFF – Identify Friend or Foe)

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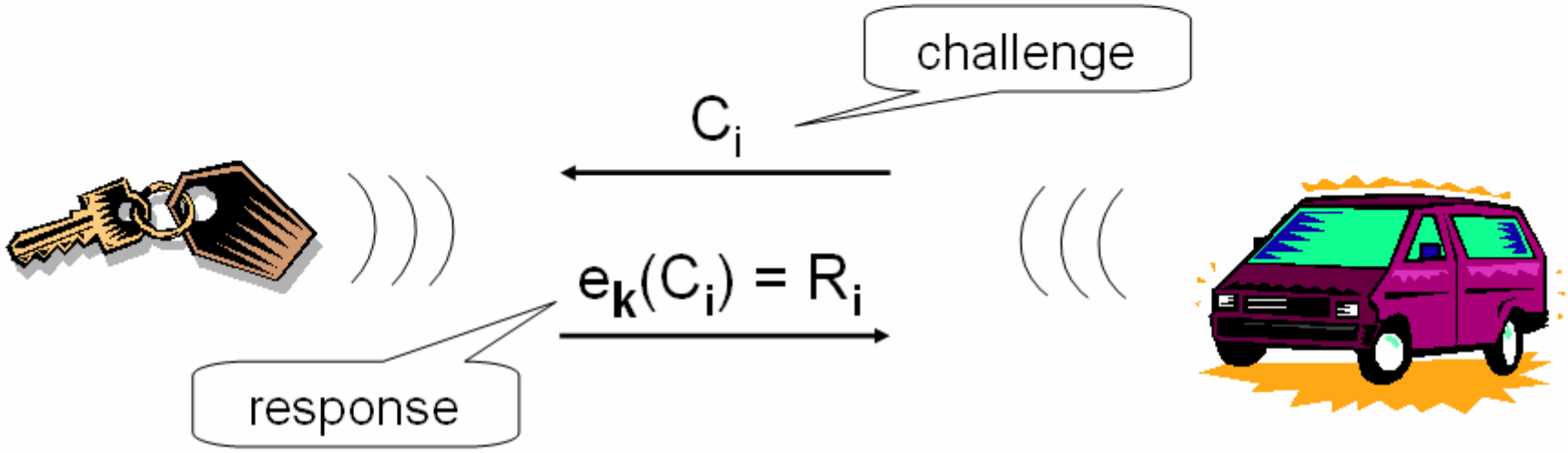

- again, $e_k()$ is often a block cipher
- also protects against replay attack
- € drawback: requires bidirectional devices on either side
- In most real-world car and building access control systems: rolling code

1. Computes: $R'_i = e_k(C_i)$
2. Verifies: $R'_i \stackrel{?}{=} R_i$

Popular Remote Keyless Entry Cipher: KeeLoq

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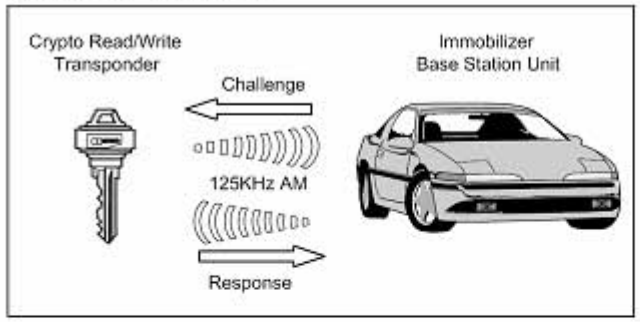
HCS410 IMMOBILIZER TRANSPONDER



KEELOQ CODE HOPPING

- KeeLoq can be used as rolling code or in a challenge-response protocol
- active remote control for access control
- KeeLoq chip embedded in passive RFID – transponder (e.g. for car immobilizer)
- Wikipedia (?):
  Chrysler, Daewoo, Fiat, GM, Honda, Toyota, Volvo, VW, Jaguar, ...
- widely used for **garage doors** in US & Europe

Q: How secure is KeeLoq?

KeeLoq Rolling Code Scheme

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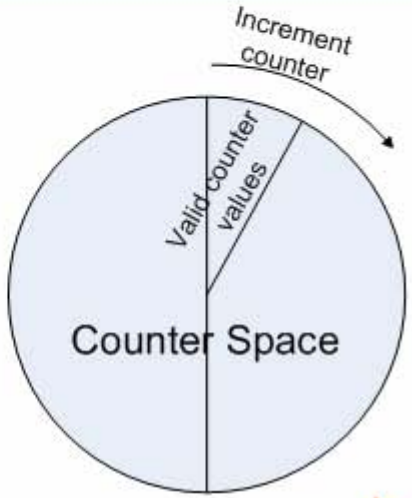
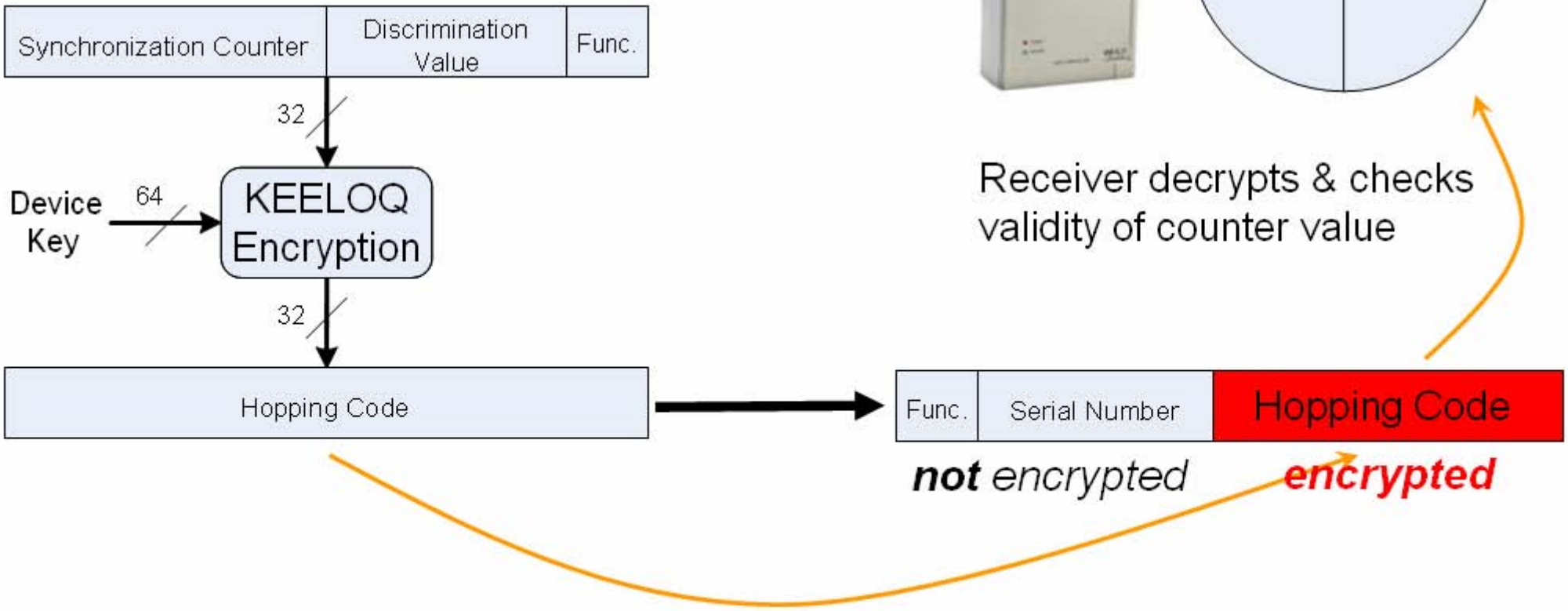
Counter: n+1



Receiver decrypts & checks validity of counter value



Key Management

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

1) Creation of new remote (in secure environment)

k_M

#ser

$k_{dev} = f(\#ser, k_M)$

Key derivation

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

#ser

k_M

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

Key Derivation Schemes

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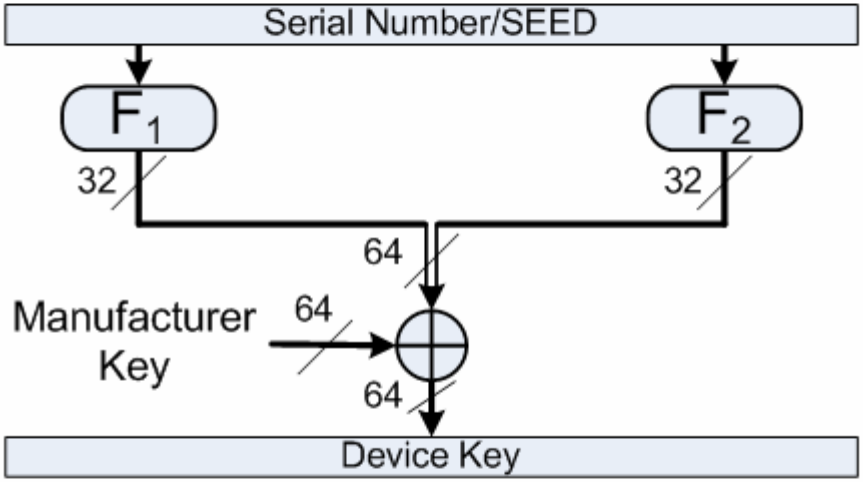
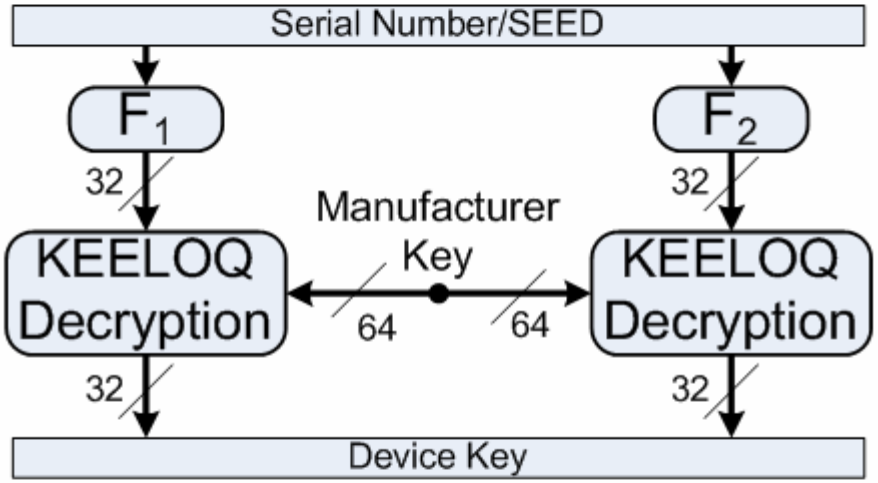
1. Weak Key Derivation (XOR)



2. Strong Key Derivation (KeeLoq)



In either case, device key is derived from:

- Manufacturer key
- Serial number (known) or Random seed (32…60bits)

Key Derivation: Attacker's Assessment

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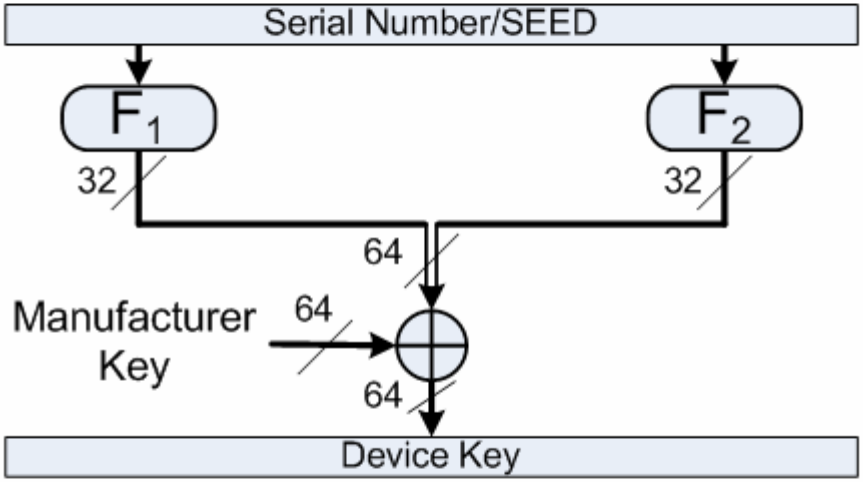
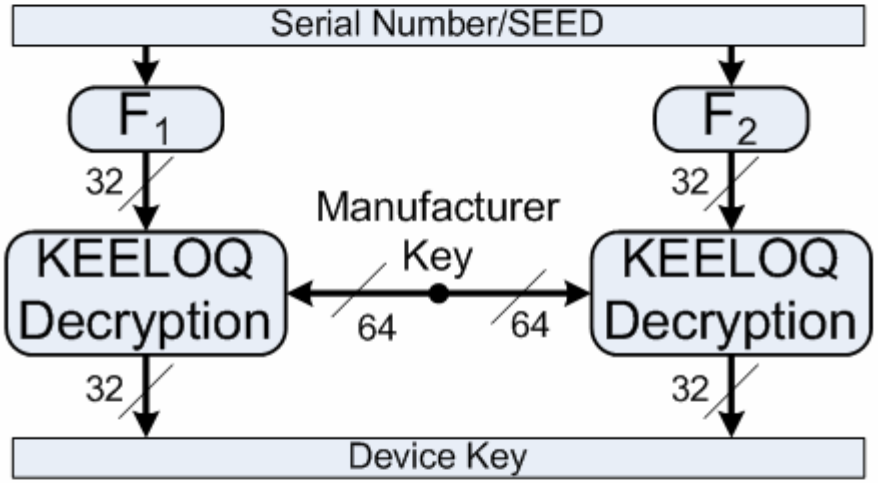
1. Weak Key Derivation (XOR)



If we have the Device Key, getting the Manufacturer Key is trivial (and vice versa)

2. Strong Key Derivation (KeeLoq)



If we have the Device Key, we still have to break KeeLoq

Rise and Fall of KeeLoq

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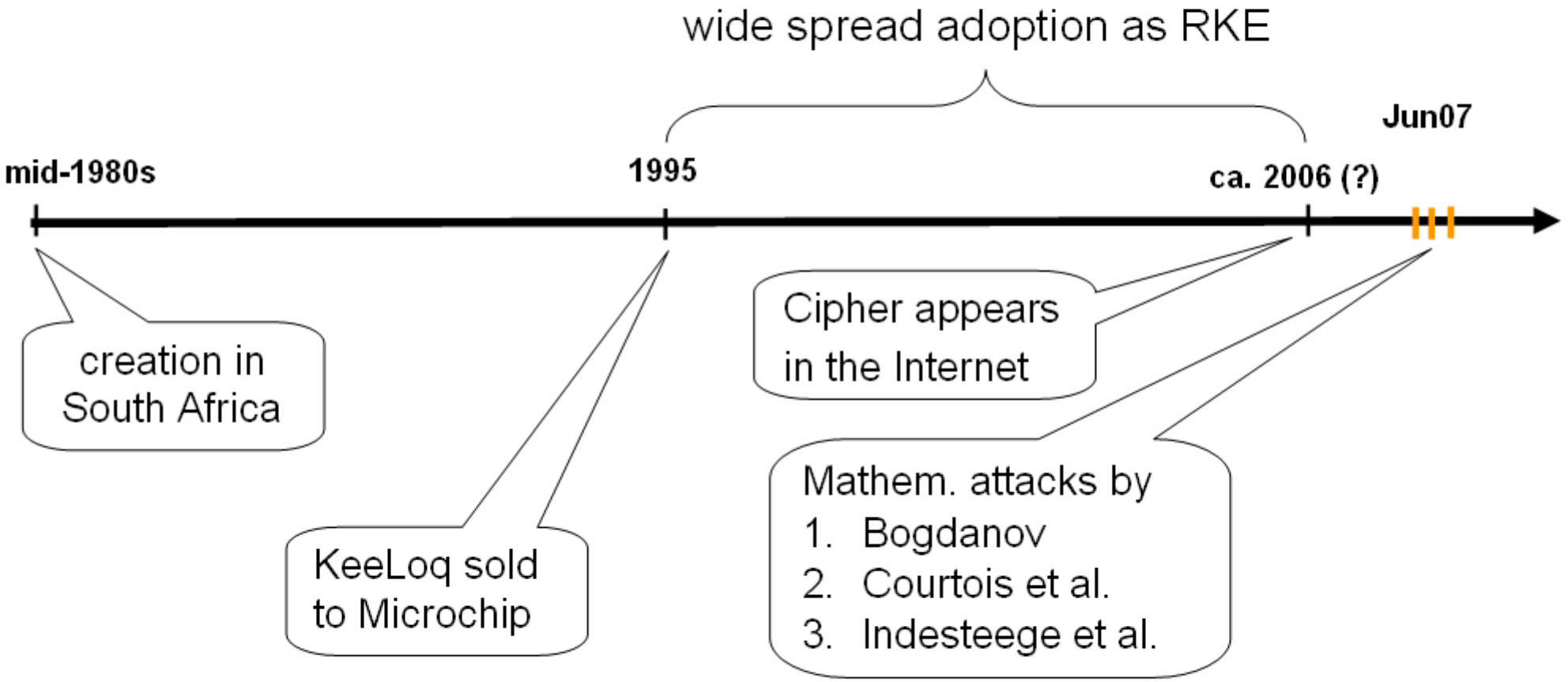

Mathematical Attacks: Recovery of Manufacturer Key

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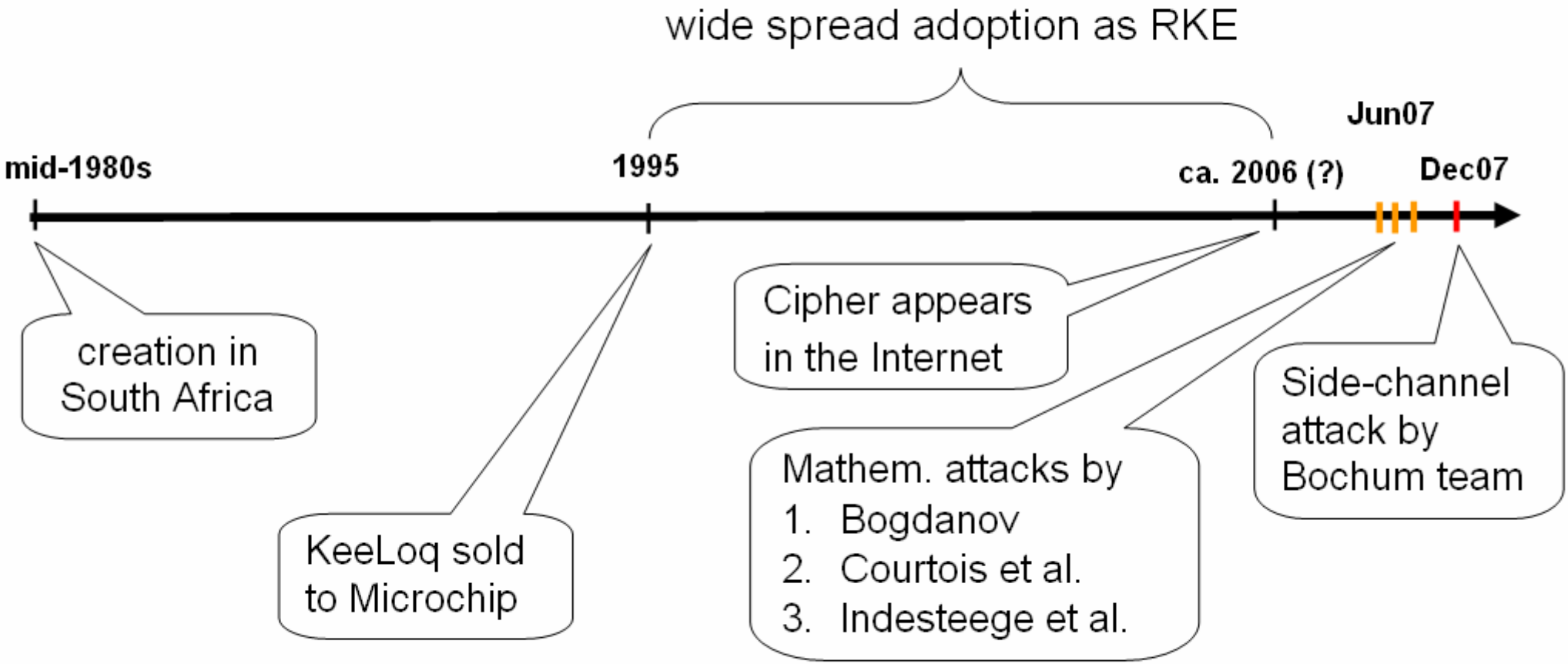
	XOR Key Derivation	KeeLoq Key Derivation
Challenge-Response	Y	N
Rolling Code	N	N

- Mathematical attacks are 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?**

Rise and Fall of KeeLoq



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

Power Analysis of Remote Control

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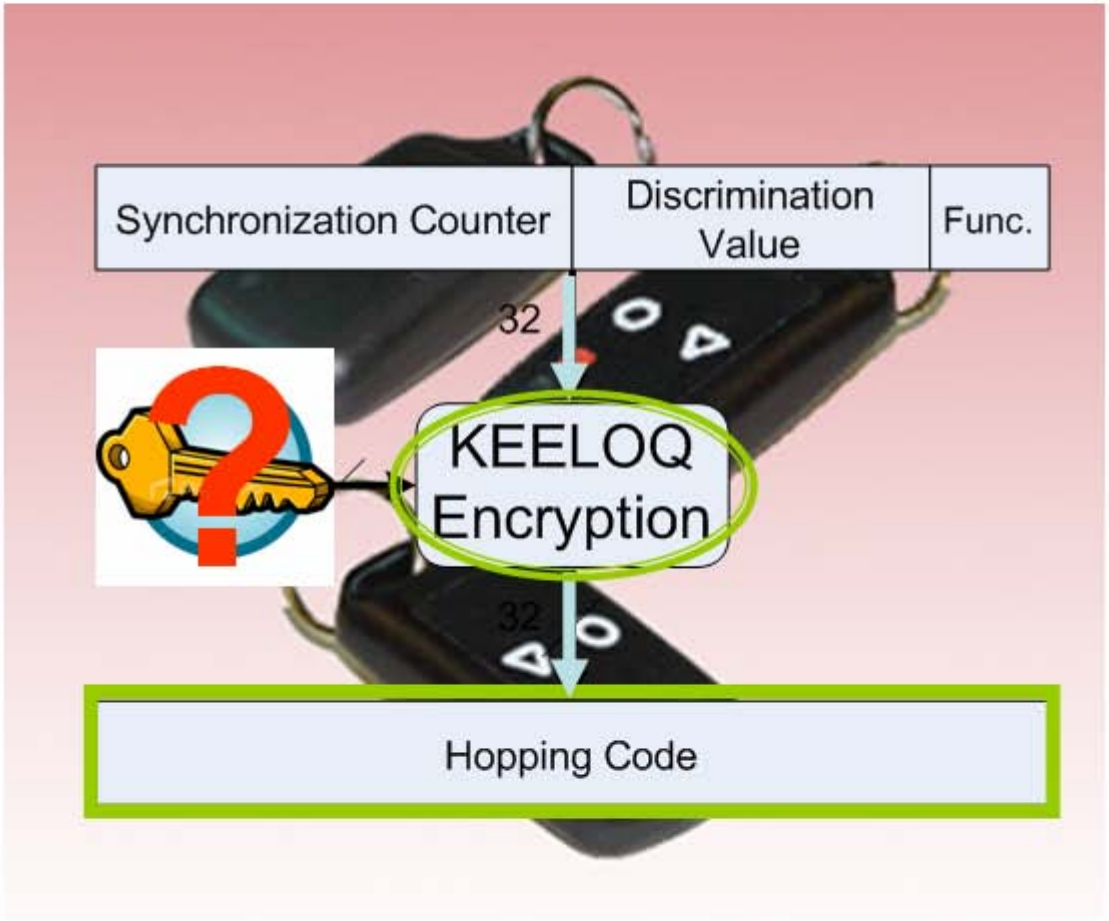

Power Analysis of Remote Control

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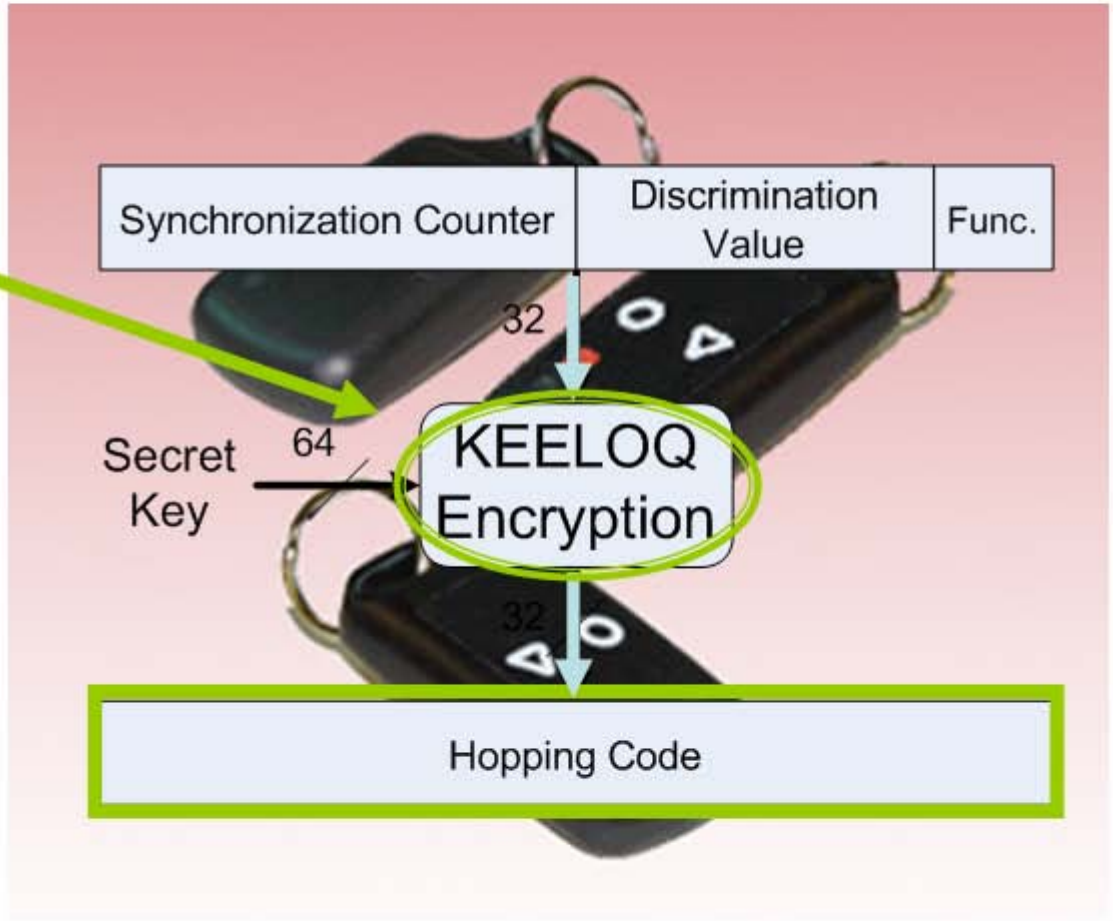
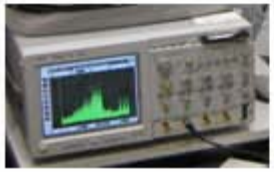


secret key of remote control (HCS XXX Chip) !

Performing the Side-Channel Attack



Analyze cipher

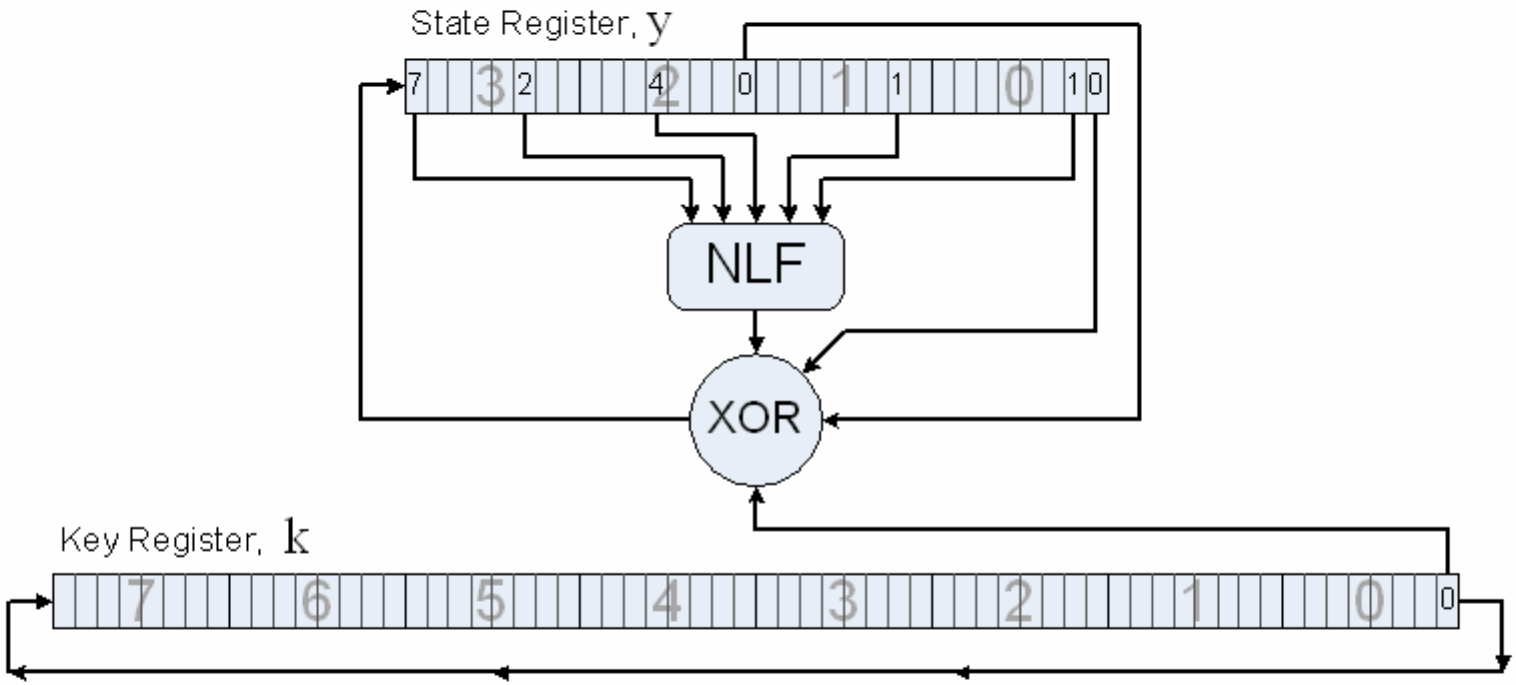
Measurements

Post Processing

Key Recovery

1. Find a suited predictable intermediate value in the cipher
2. Measure the power consumption
3. Align and reduce size of acquired data
4. Correlate measurements with model

KeeLoq – Algorithm



- 64 bit key, 32 bit block length
- NLFSR comprising a 5x1 non-linear function
- Simple key management: key is rotated in every clock cycle
- 528 rounds, each round one key bit is read

→ Lightweight cipher – cheap and efficient in hardware

KeeLoq – Power Model

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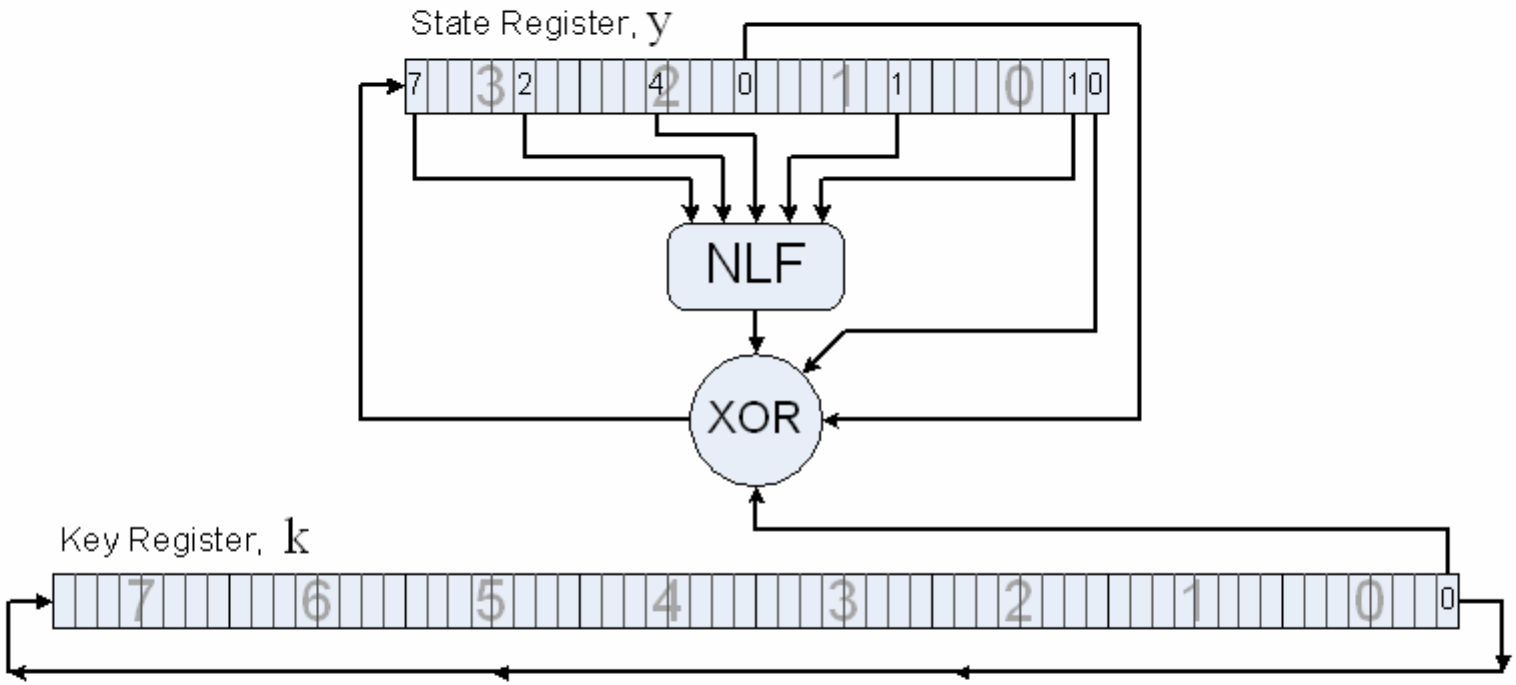
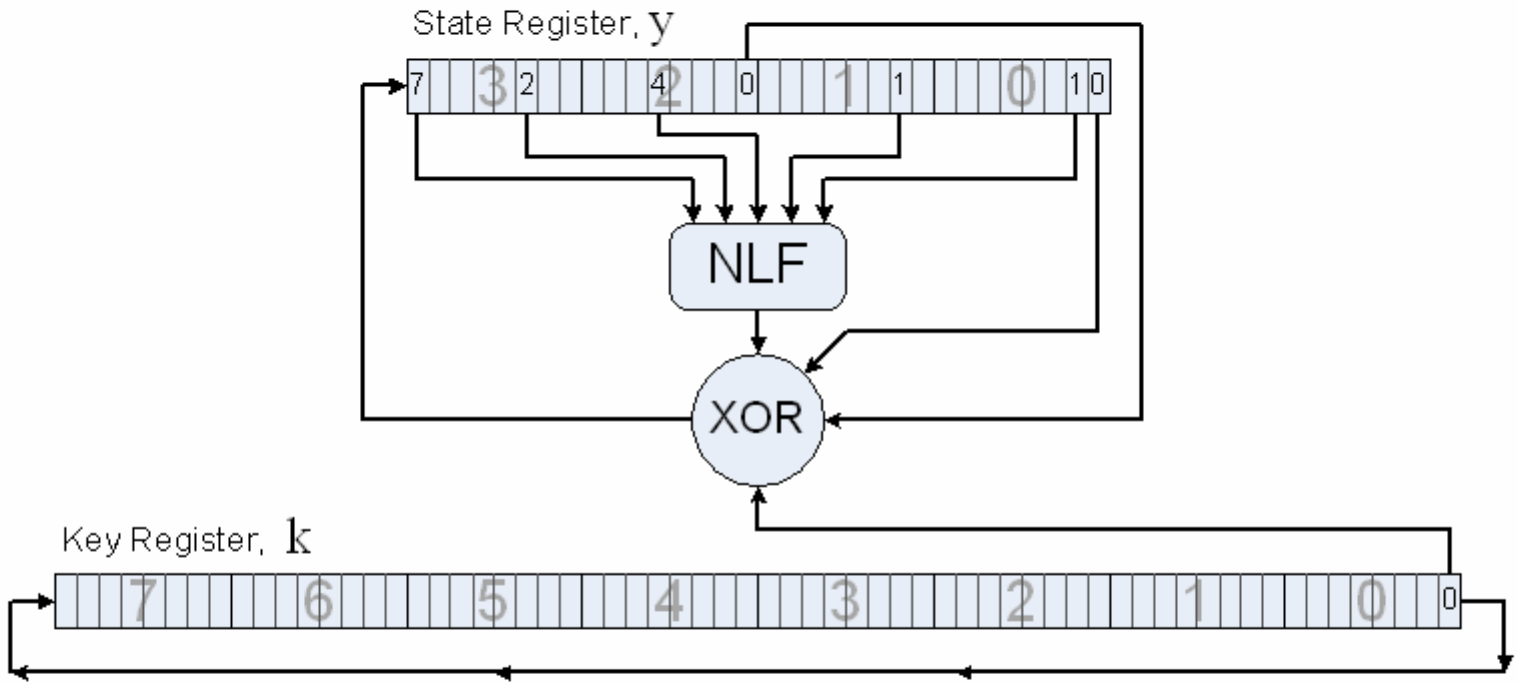


- Software: typically leaks Hamming weight (HW)
- Hardware: typically leaks Hamming distance (HD)

$$\mathrm{P}_{Hyp}^{(i)} = \mathrm{HD}\left(\boldsymbol{y}^{(i)}, \boldsymbol{y}^{(i-1)}\right) = \mathrm{HW}\left(\boldsymbol{y}^{(i)} \oplus \boldsymbol{y}^{(i-1)}\right)$$

KeeLoq – Power Model

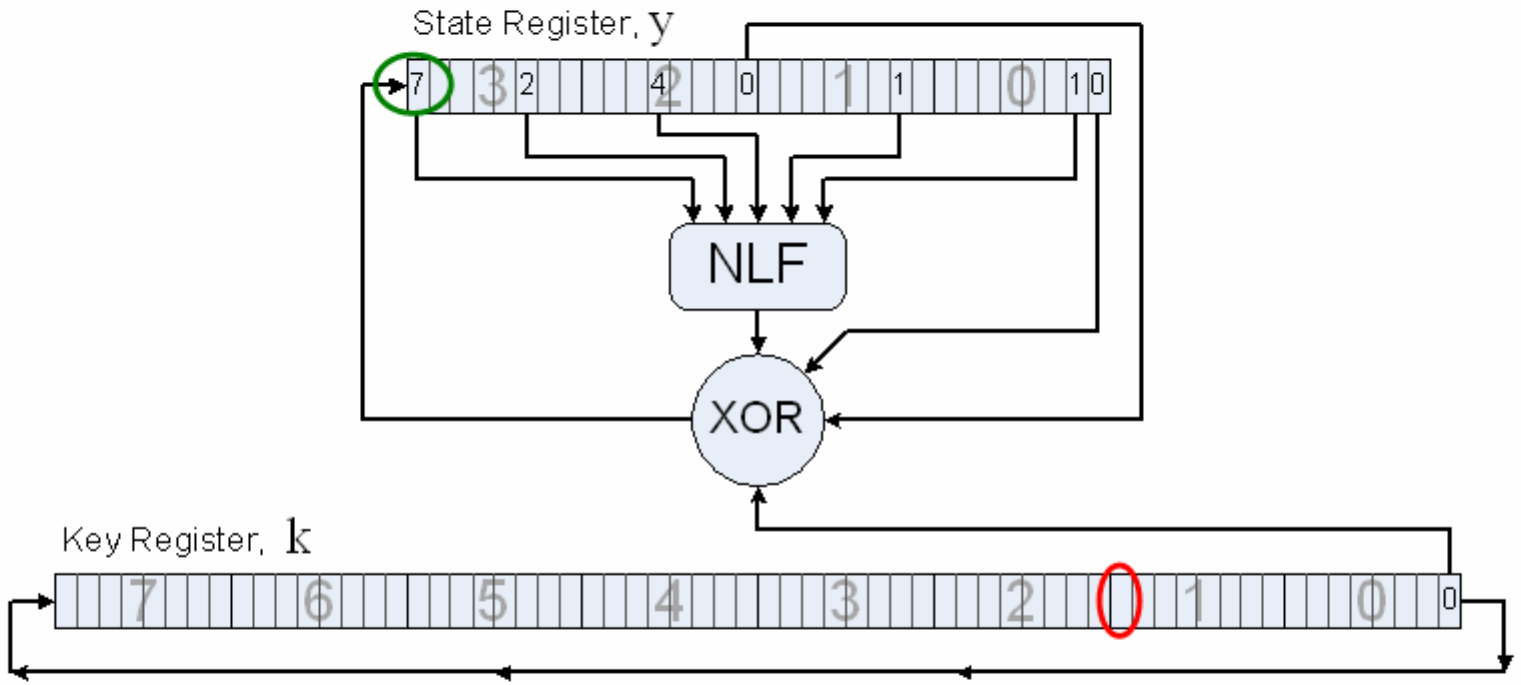


Power Consumption:

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

→ **Variations** of power consumption are related to State Register

KeeLoq – Attack

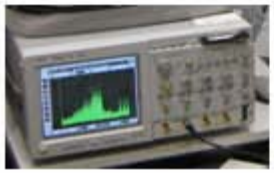


$$y_{31}^{(i+1)} = k_0^{(i)} \oplus y_{16}^{(i)} \oplus y_0^{(i)} \oplus \mathrm{NLF}\left(y_{31}^{(i)}, y_{26}^{(i)}, y_{20}^{(i)}, y_9^{(i)}, y_1^{(i)}\right)$$

$$y_0^{(527)} = k_{15} \oplus y_{16}^{(527)} \oplus y_{31}^{(528)} \oplus \mathrm{NLF}\left(y_{31}^{(527)}, y_{26}^{(527)}, y_{20}^{(527)}, y_9^{(527)}, y_1^{(527)}\right)$$

→ knowing the state directly reveals one key bit per clock cycle

Performing the Side-Channel Attack



Analyze cipher

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Measuring the Power Consumption

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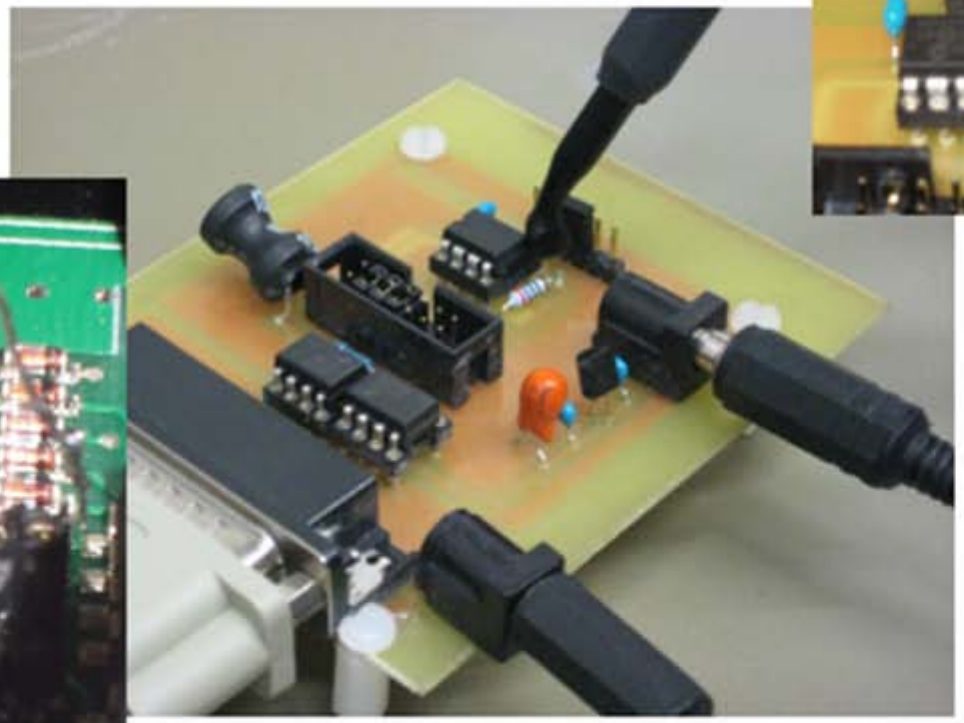
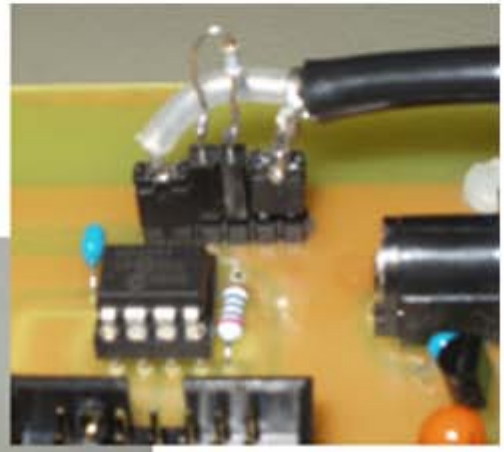
- Digital oscilloscope (max. 1 GS/s sample rate)
- Measure electric current or electromagnetic field





Power Trace of a remote control: Finding the KEELOQ - Encryption

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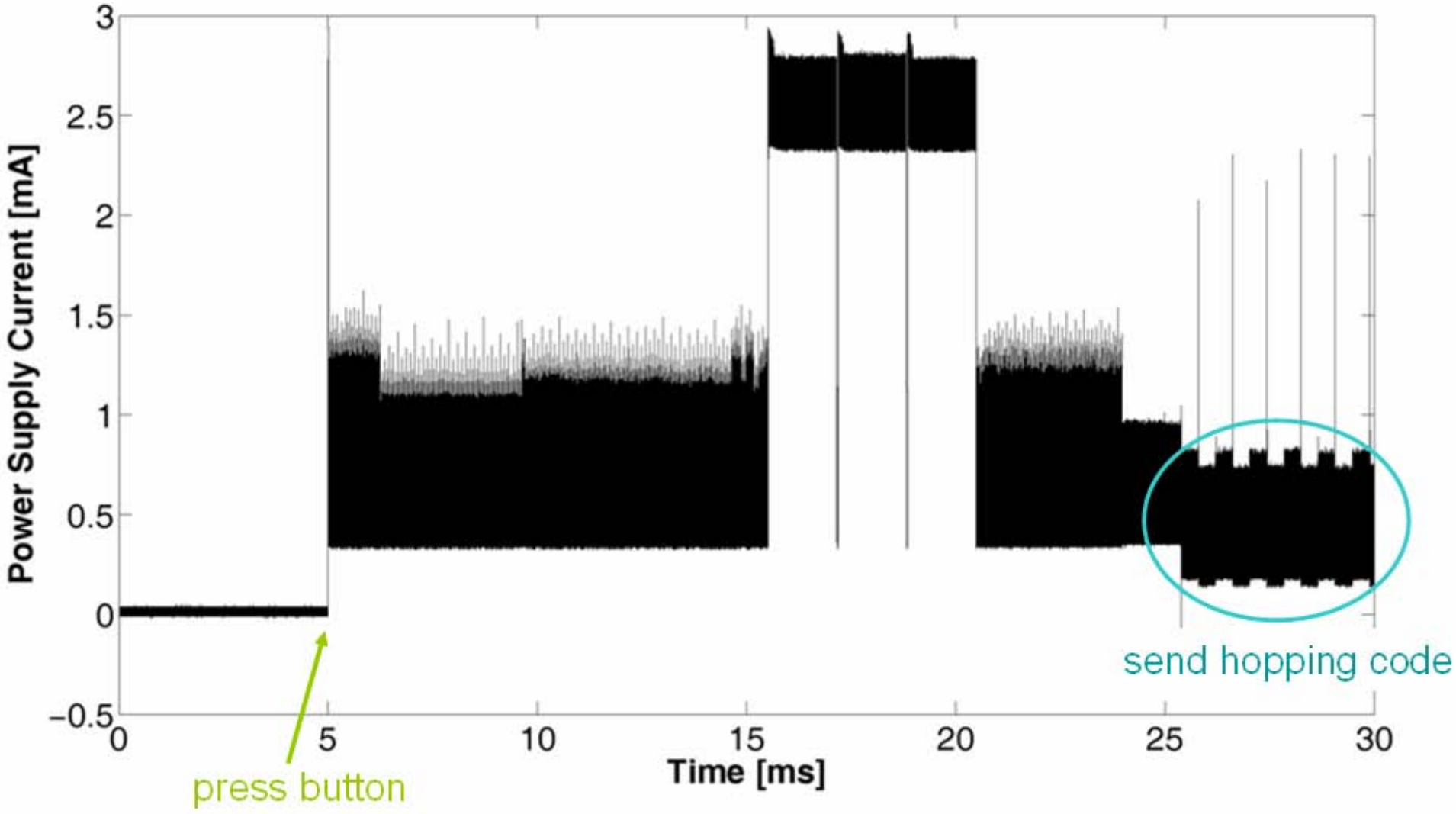
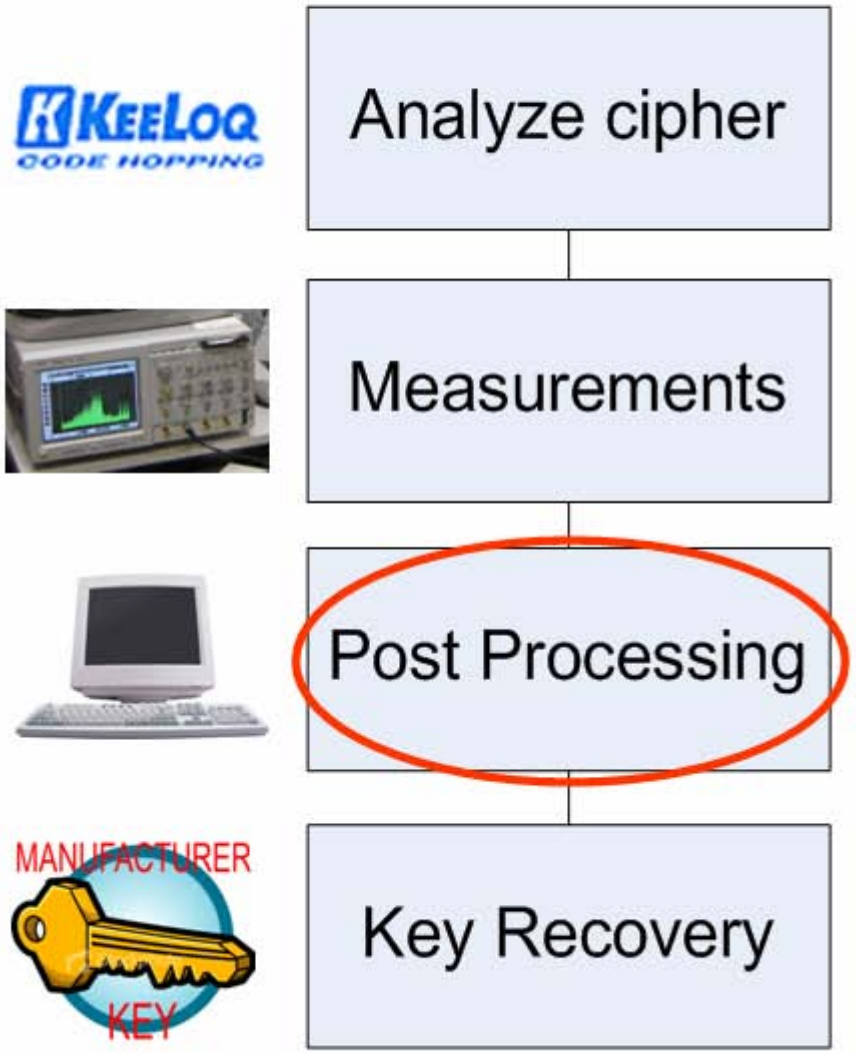


Performing the Side-Channel Attack



1. Find a suited predictable intermediate value in the cipher
2. Perform power measurements
3. Align and reduce size of acquired data
4. Correlate measurements with model

Performing the Side-Channel Attack
Post Processing

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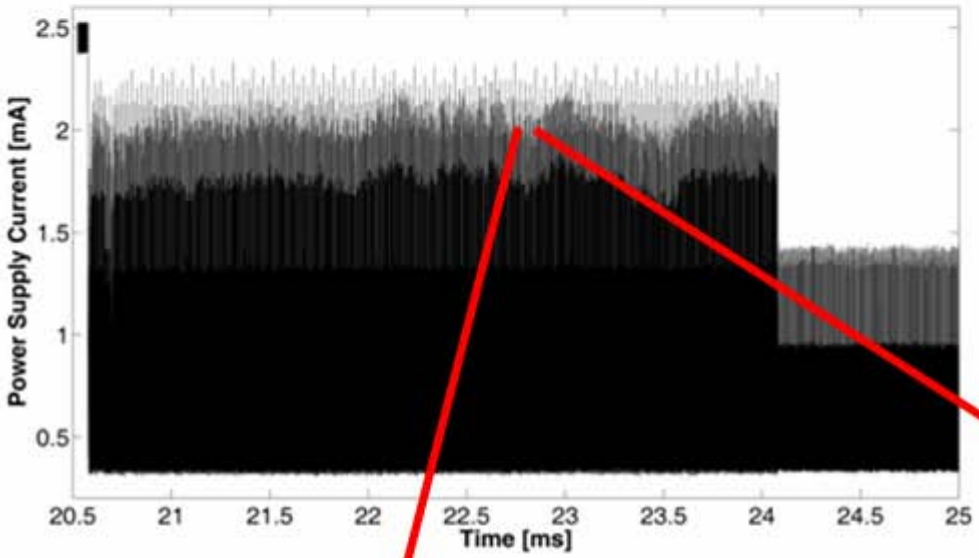
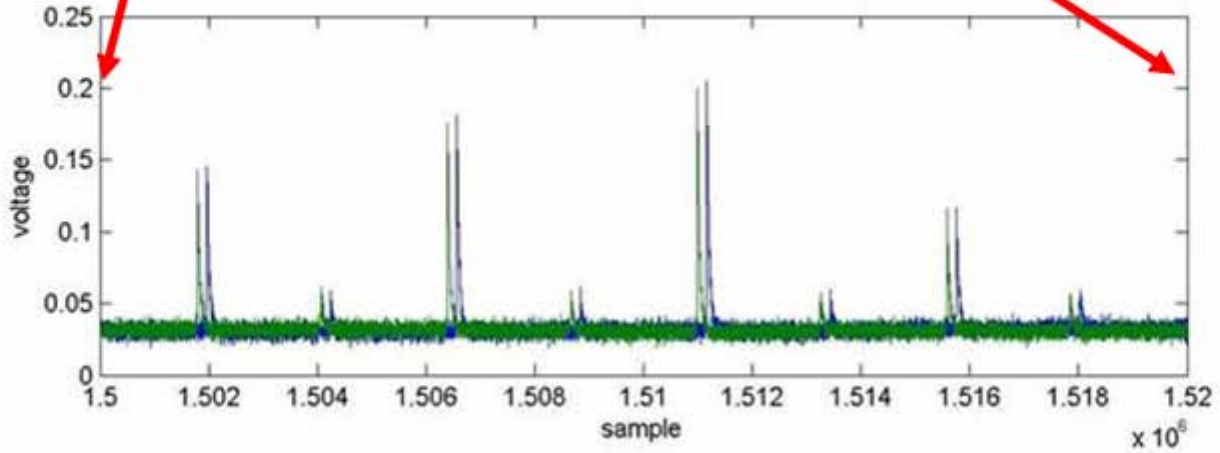


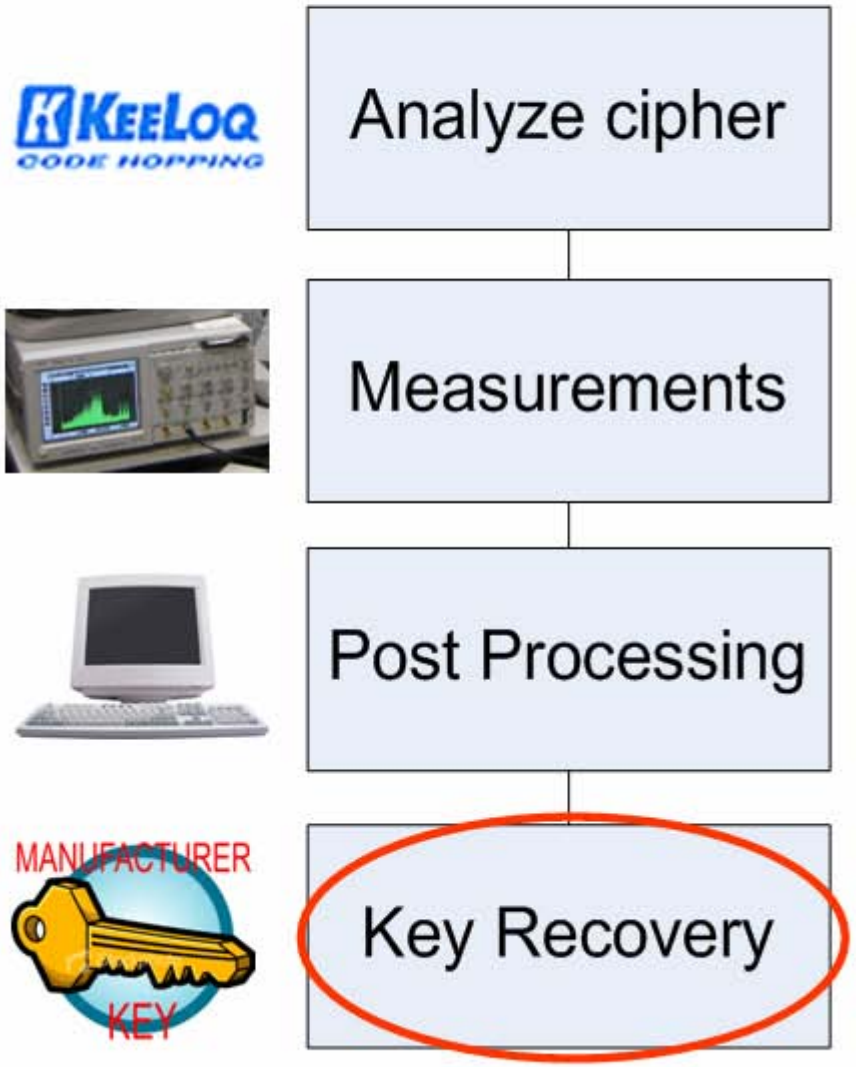
Problems:

- Alignment
- Clock jitter introduces noise
- Traces are very large

Peak detection takes care of **alignment** and **reduces size** of traces!



Performing the Side-Channel Attack



1. Find a suited predictable intermediate value in the cipher
2. Perform power measurements
3. Align and reduce size of acquired data
4. Correlate measurements with model

Performing the Side-Channel Attack
Key Recovery

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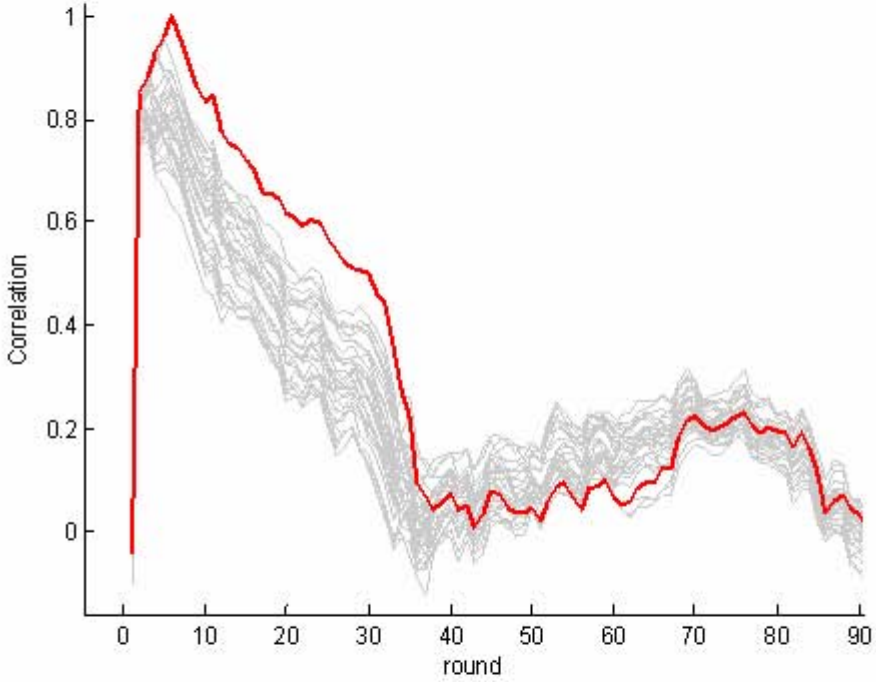
- Correlate power consumption to predicted value $D = f(X_i, K_h)$
- Divide and conquer approach
- Let the best-matching key candidates "survive"



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

Power Analysis of the Receiver

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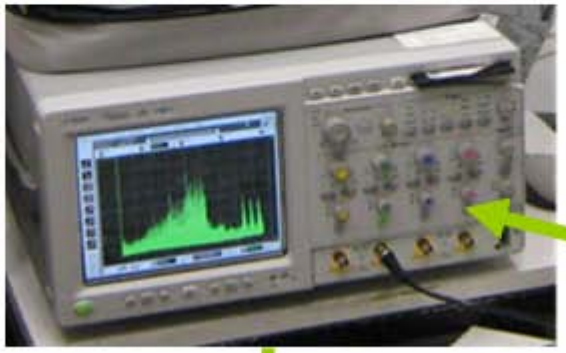

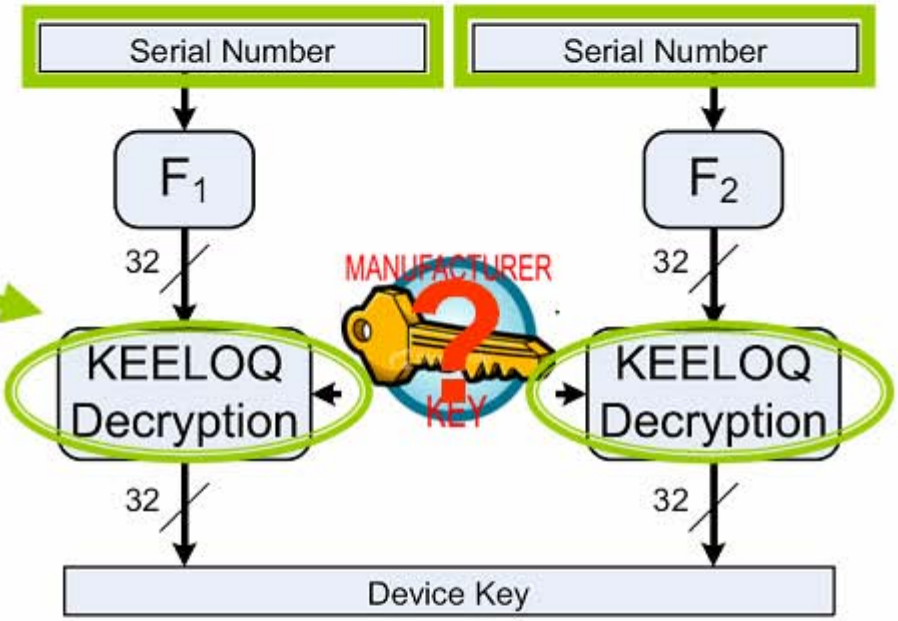

secret key of manufacturer!

Side-Channel Attack Results for KeeLoq

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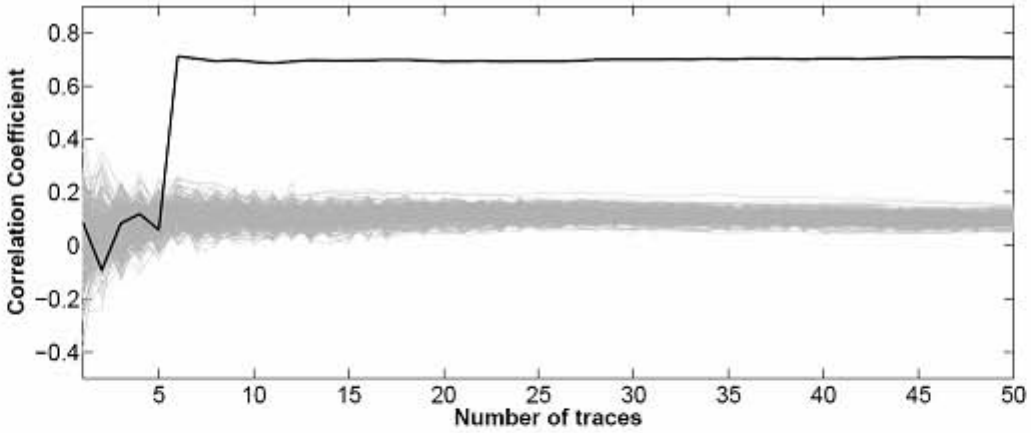
A) Hardware implementation ("car key")

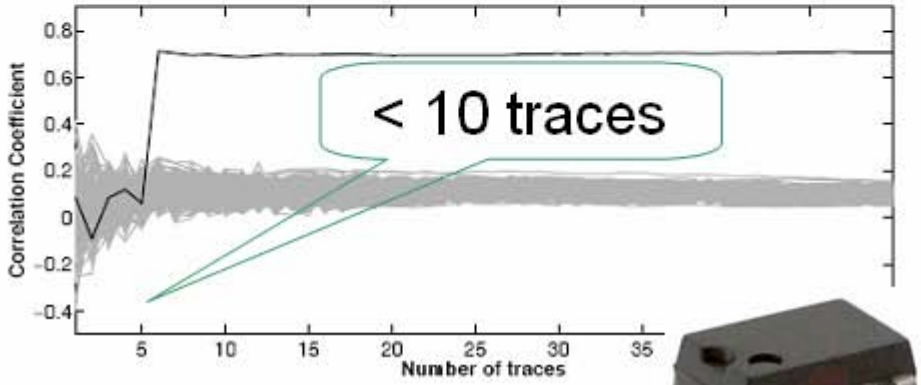
- Total attack time (for known device family):
  5-30 traces, ≈ minutes



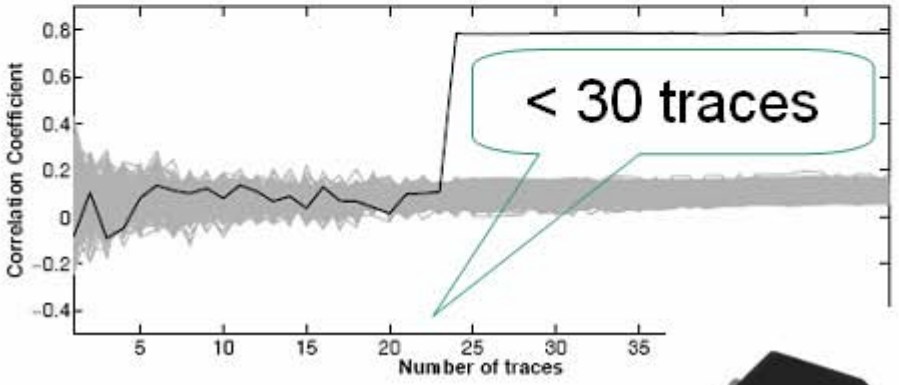
B) Software implementation ("car door")

- Total attack time (for known device family):
  1000-5000 traces, ≈ hours
- reveals Manufacturer Key for ALL key derivation modes

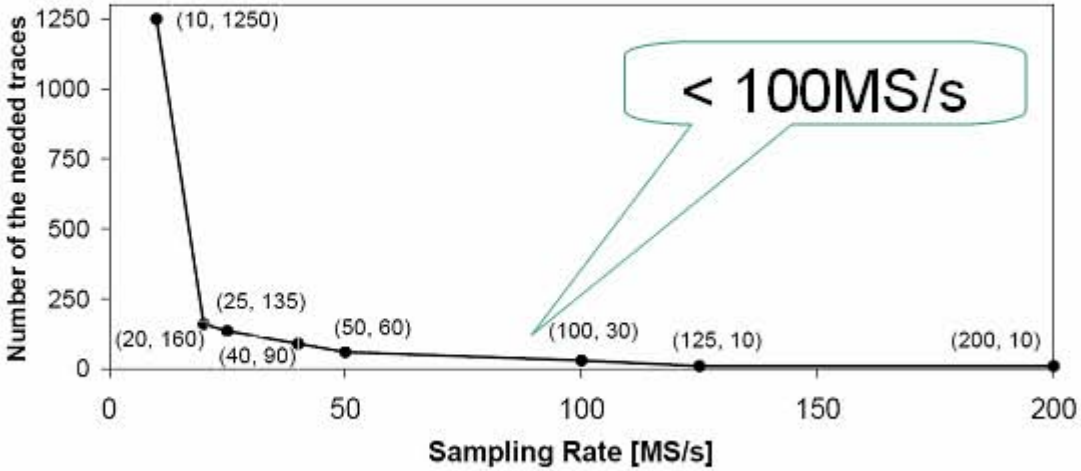
Comparison of Packages & Sample Rates



(a) DIP



(b) SOIC



No expensive equipment needed for key recovery !

So what can we do now (1) ?

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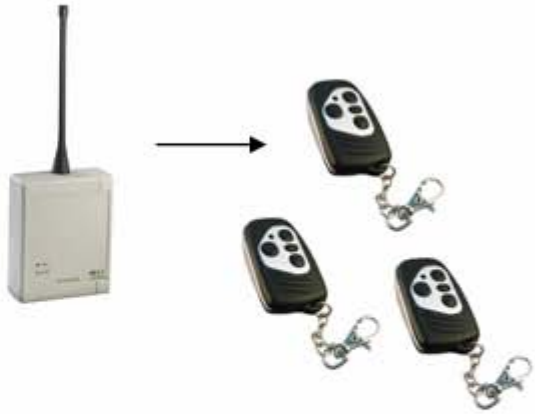
1. If we have access to a remote:

   Recover Device Key and clone the remote

2. If we have access to a receiver:

   Recover Manufacturer Key & generate new remotes



So what can we do now (2) ?

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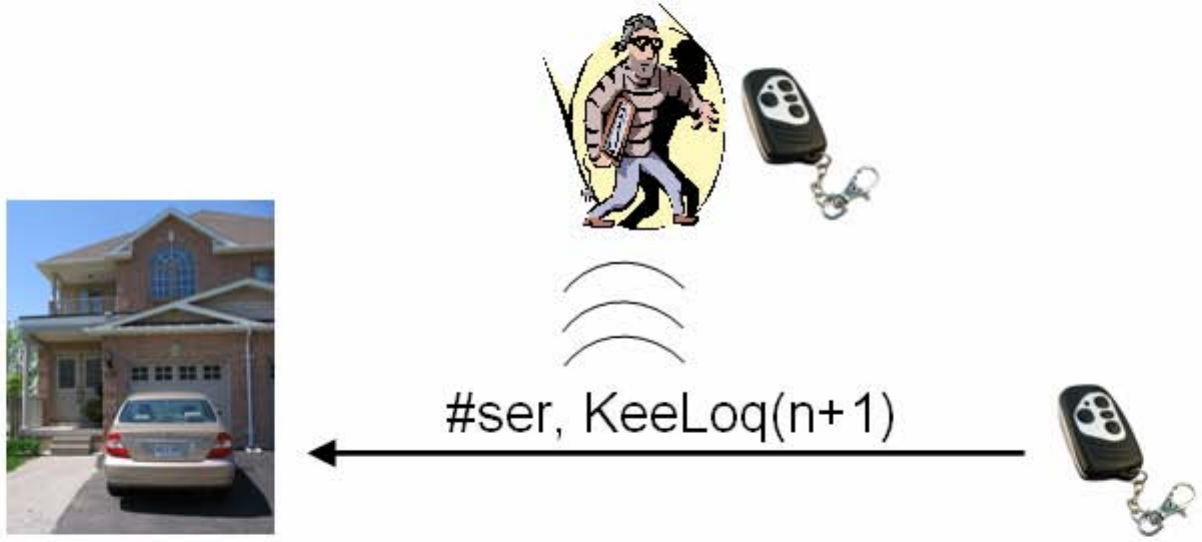
3. After step 2 (i.e., possessing the Manufacturer Key):
   Remotely eavesdrop on 1-2 communications & clone remote!



www.copacobana.org

- works for all key derivation schemes
- **instantly** for key derivation from serial number
- otherwise use PC (short seed) or COPACOBANA (long seed)

Details on Eavesdropping Attack

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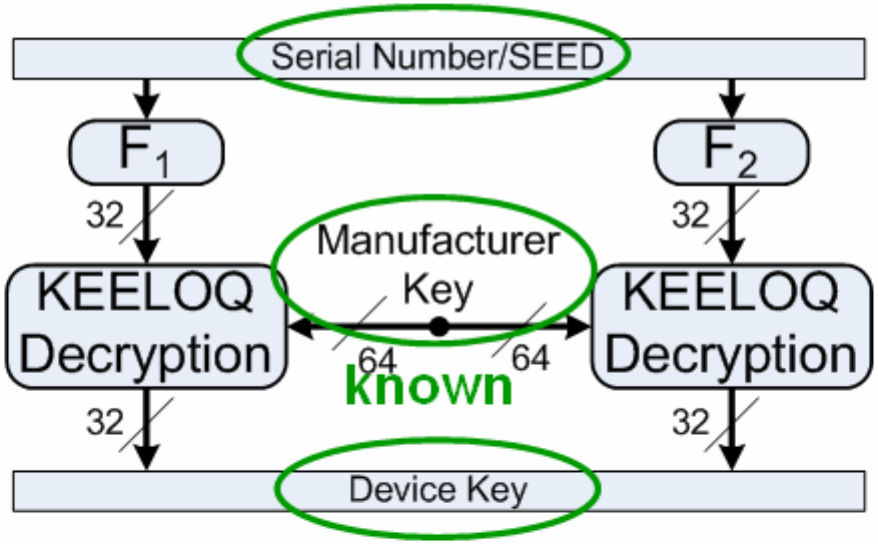
Possessing the Manufacturer Key:

Remotely eavesdrop on 1-2 communications, and clone Device Key!

known(Serial) or brute-forced(Seed)



…easy.

1. Recover Device Key
2. Decrypt Rolling Code → obtain counter etc.
3. Clone the remote control

Details on Eavesdropping Attack

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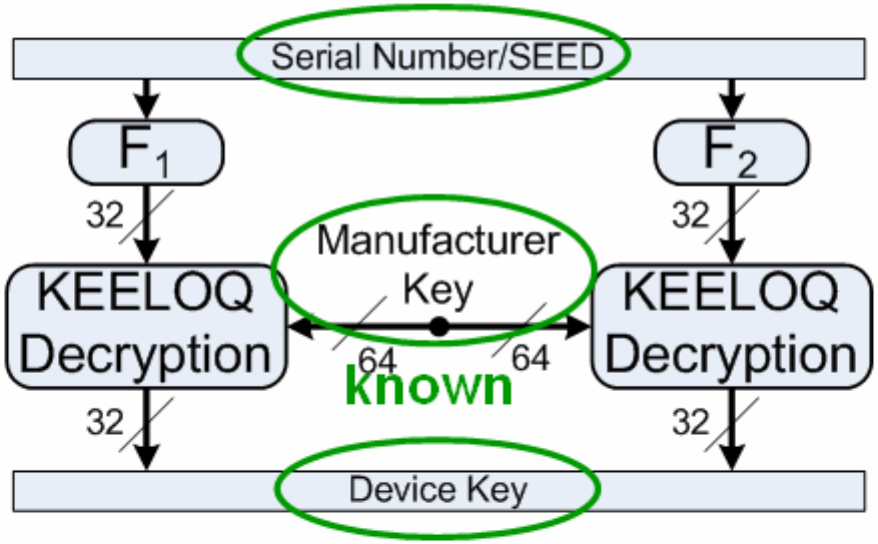
Possessing the Manufacturer Key:

Remotely eavesdrop on 1-2 communications, and clone Device Key!

known(Serial) or brute-forced(Seed)



...easy.

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

Taking over a KeeLoq System

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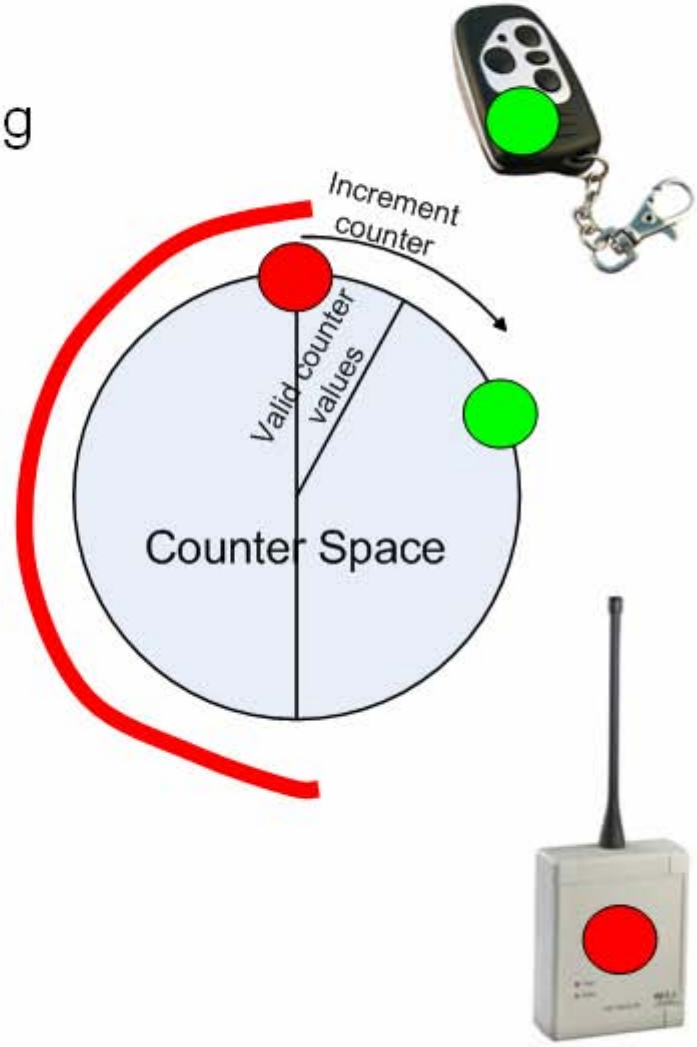
- Receiver updates its internal counter according to the last received valid Rolling Code

Block Window



Taking over a KeeLoq System

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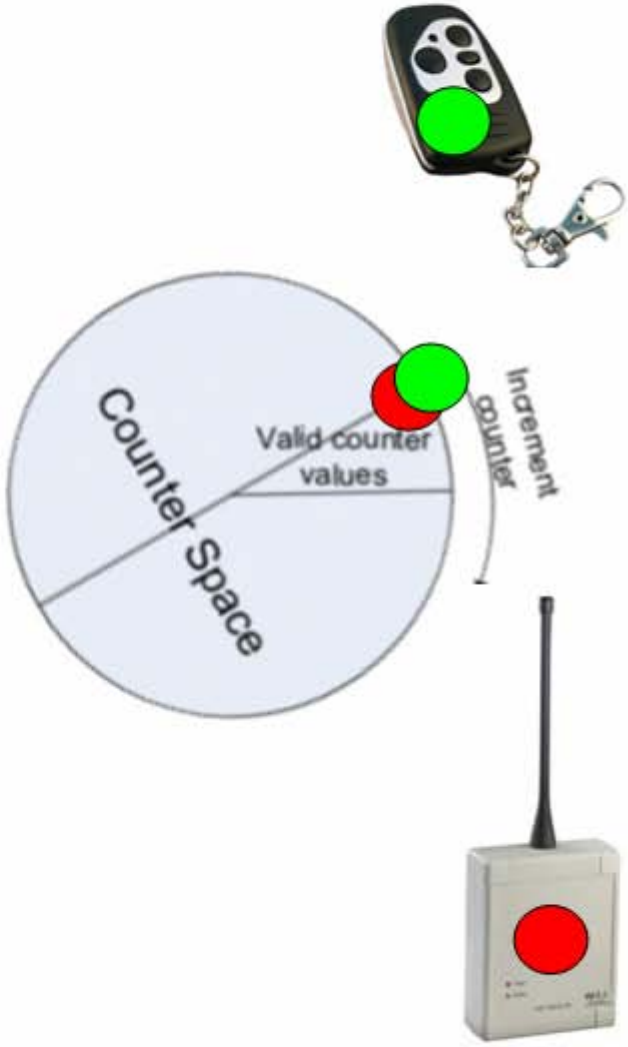
- Receiver updates its internal counter according to the last received valid Rolling Code



Taking over a KeeLoq System

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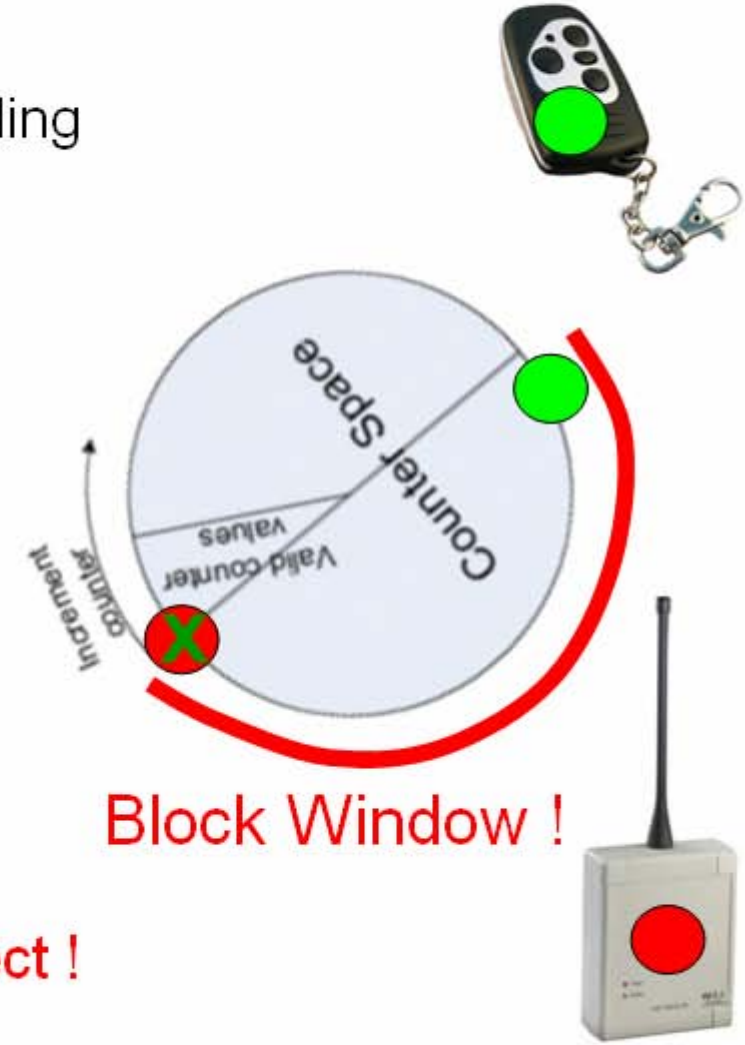
- Receiver updates its internal counter according to the last received valid Rolling Code

- Generate valid Rolling Code with chosen counter value

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

- Attacker can still access the secured object !



Summary

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- "Security by Obscurity" makes insecure systems
- DPA works for commercial access control system
- some severe attacks can be done by non-specialists

- side-channel attacks are a real threat for **all** unprotected implementations of cryptography (ECC, AES, …)
- we have to put SCA-resistance in many devices, including embedded / consumer-style applications

Disclaimer: Our attacks do **not** imply that real-world systems have actually been attacked via SCA by criminals (merely by researchers).

Literature

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