EURECOM
Sophia Antipolis

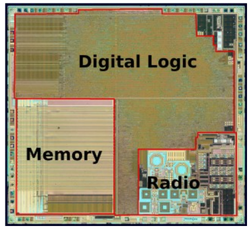
Understanding Screaming Channels: From a Detailed Analysis to Improved Attacks

Giovanni Camurati*, Aurélien Francillon*, François-Xavier Standaert**
*EURECOM, **Université catholique de Louvain

Who am I?

Giovanni Camurati

Ph.D. Student at EURECOM, Sophia-Antipolis, France
@GioCamurati
https://giocamurati.github.io



Side Channels and Radios

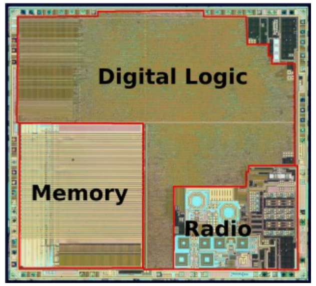
What happens if radio transceivers are close to computing devices?

Computer Architectures, Electronics, Embedded Systems

Hardware Design, Firmware Rehosting,
Hack@DAC with NOPS

Why radios and computing devices?

Modern Connected Devices Have Radios

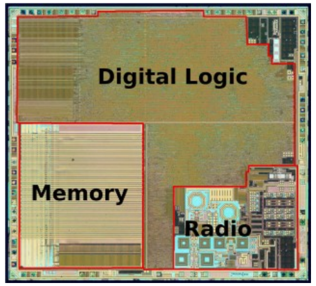


Mixed-signal architecture

CPU + Crypto + Radio

Same chip

Modern Connected Devices Have Radios



Mixed-signal architecture

CPU + Crypto + Radio

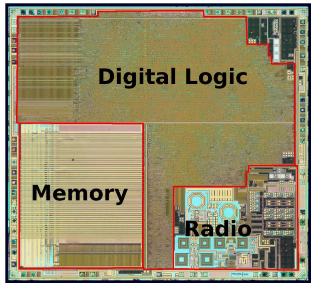
Same chip

Benefits

Low Power, Cheap, Small

Easy to integrate

Modern Connected Devices Have Radios



Mixed-signal architecture

CPU + Crypto + Radio

Same chip

Benefits

Low Power, Cheap, Small

Easy to integrate

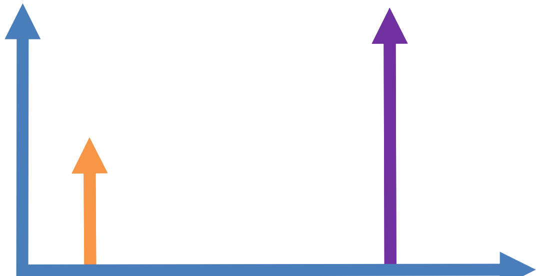
Examples

BT, BLE, WiFi, GPS, etc

What can go wrong?

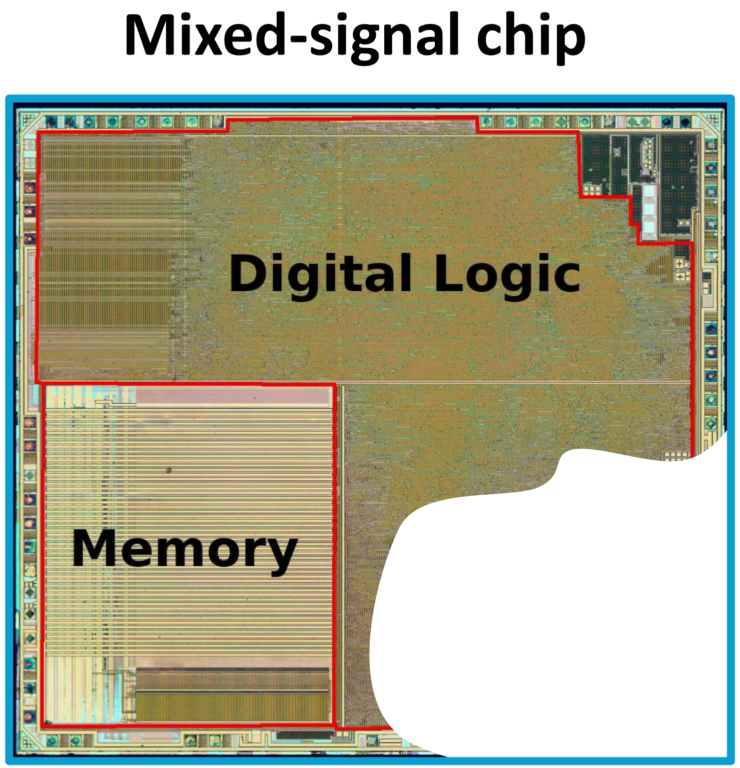
Screaming Channels [1], The Idea

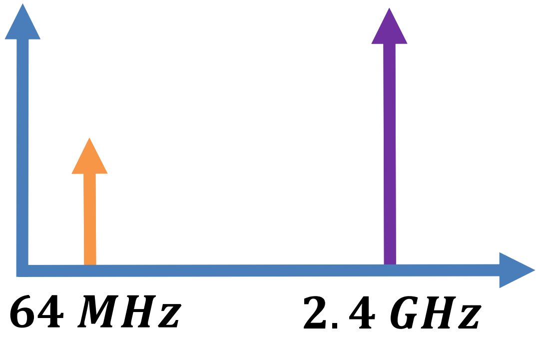
Mixed-signal chip



Screaming Channels [1], The Idea

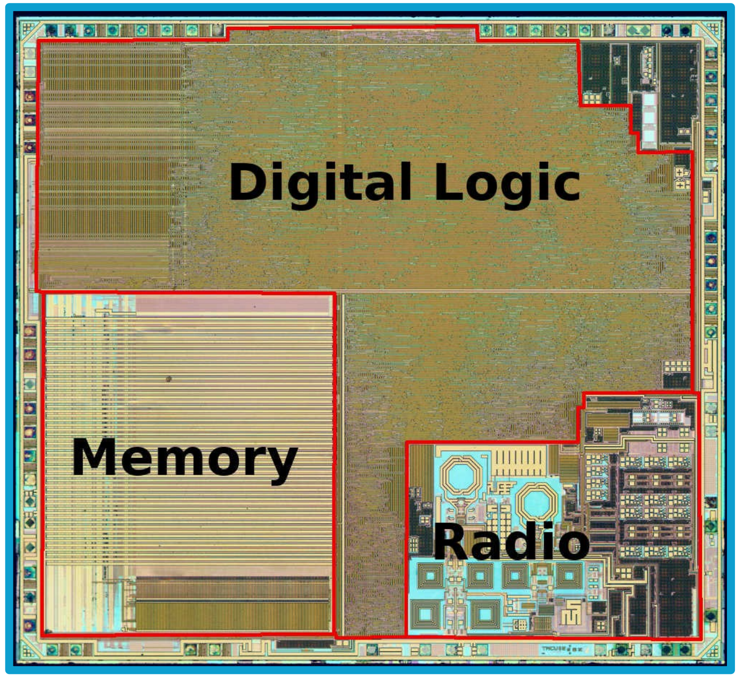
Strong noise source

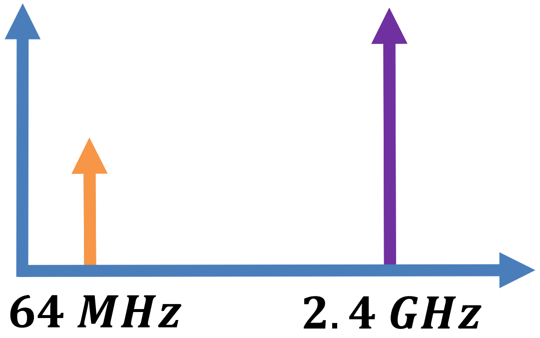




Screaming Channels [1], The Idea

Strong noise source



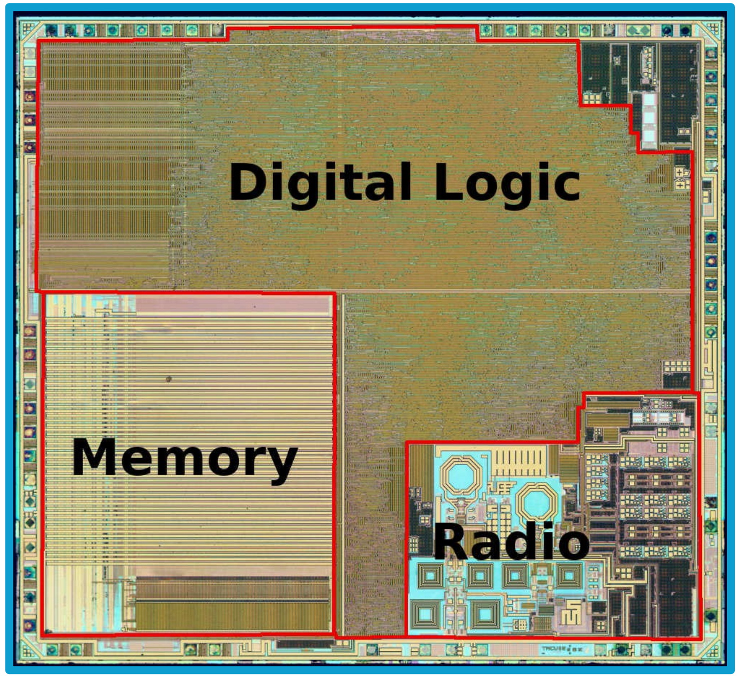


Noise sensitive transmitter

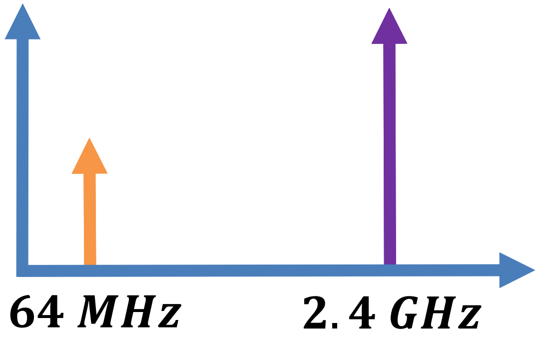
Screaming Channels [1], The Idea

Mixed-signal chip

Strong noise source



Easy propagation



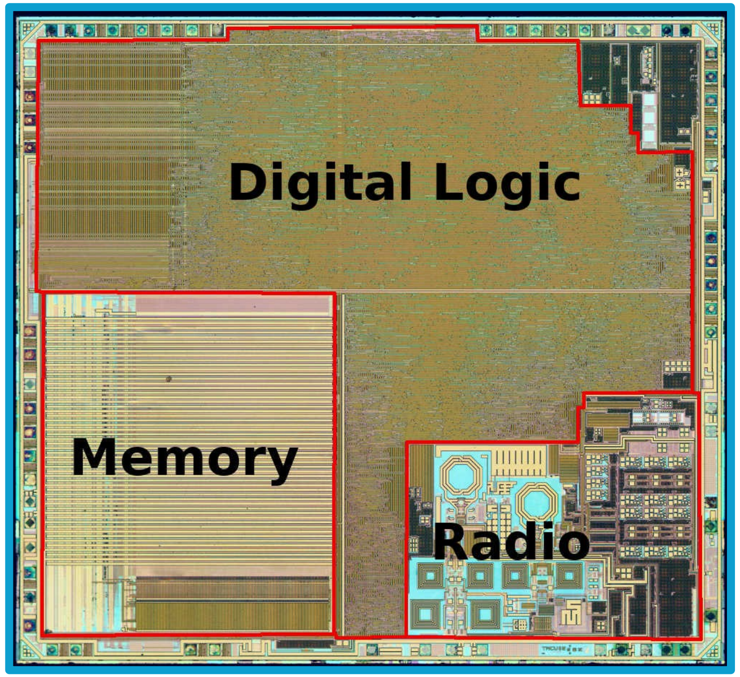
Noise sensitive transmitter

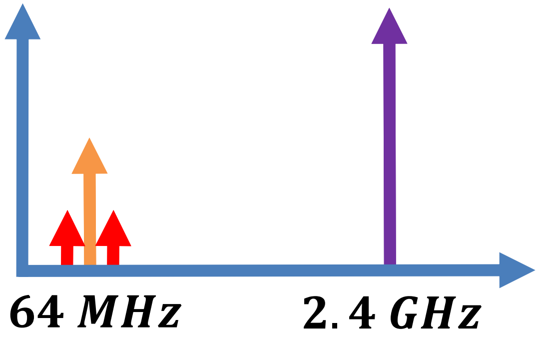
Screaming Channels [1], The Idea

Conventional Side Channel Leak

Mixed-signal chip

Strong noise source





Noise sensitive transmitter

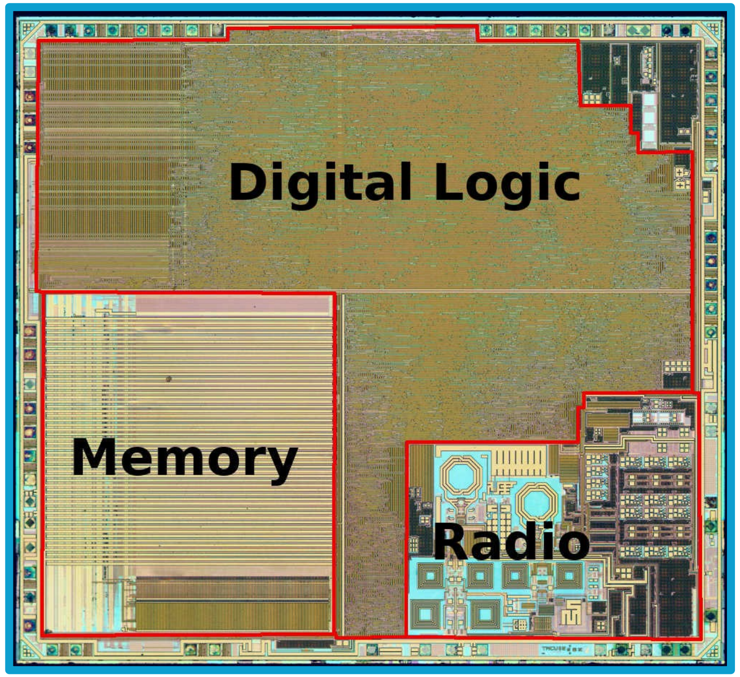
Easy propagation

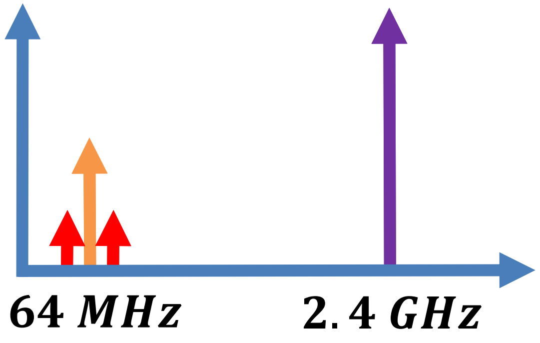
Screaming Channels [1], The Idea

Conventional Side Channel Leak

Mixed-signal chip

Strong noise source





Noise sensitive transmitter

Easy propagation

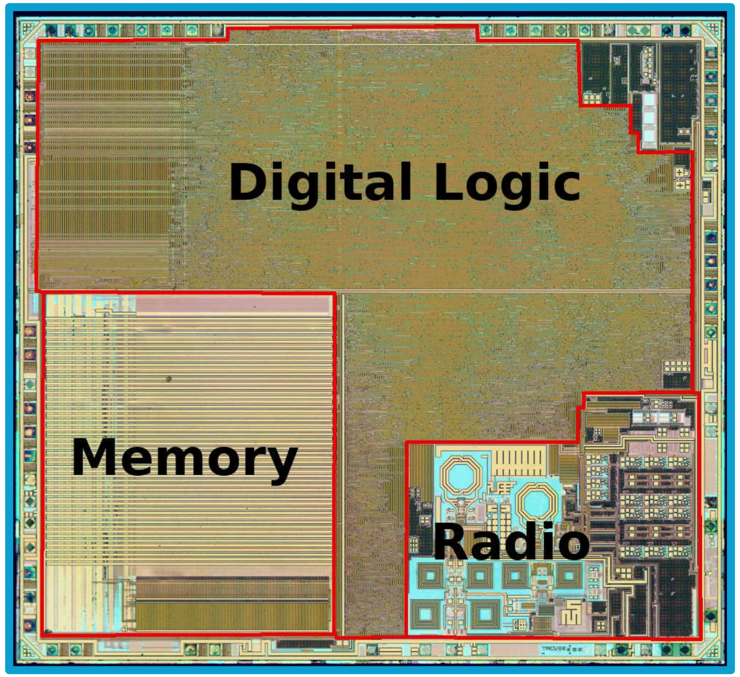
Leak Propagation

Screaming Channels [1], The Idea

Conventional Side Channel Leak

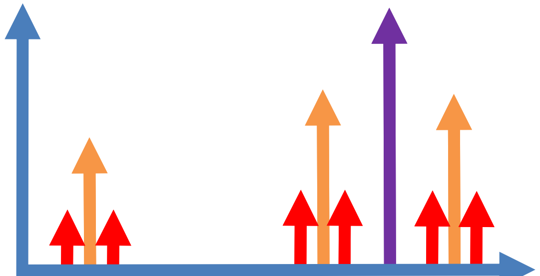
Mixed-signal chip

Strong noise source



Easy propagation

Leak Propagation

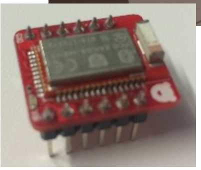


Noise sensitive transmitter

Leak Is Broadcast

Screaming Channels [1] in Action

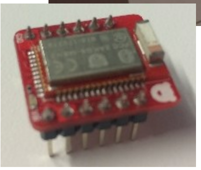
Antenna + SDR RX



Cortex-M4 + BT TX

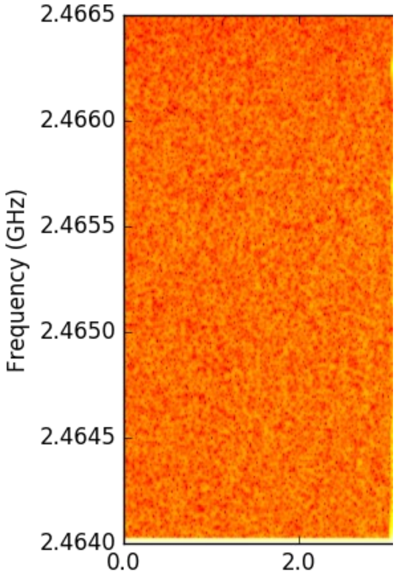
Screaming Channels [1] in Action

Antenna + SDR RX



Cortex-M4
+ BT TX

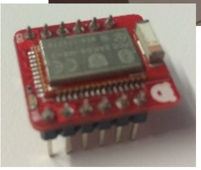
Radio Off



$\underbrace{\qquad\qquad\qquad}_{\textbf{Noise}}$

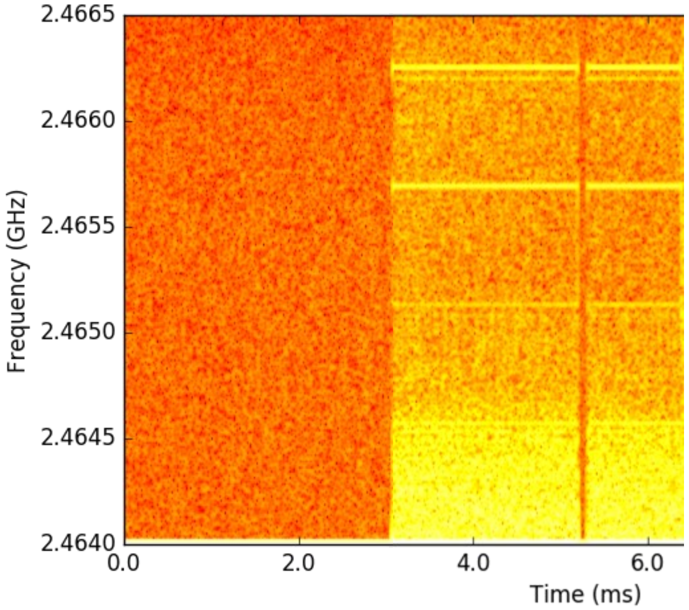
Screaming Channels [1] in Action

Antenna + SDR RX



Cortex-M4
+ BT TX

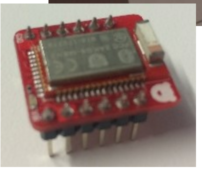
Radio Off **Radio TX**



Noise **Packet**

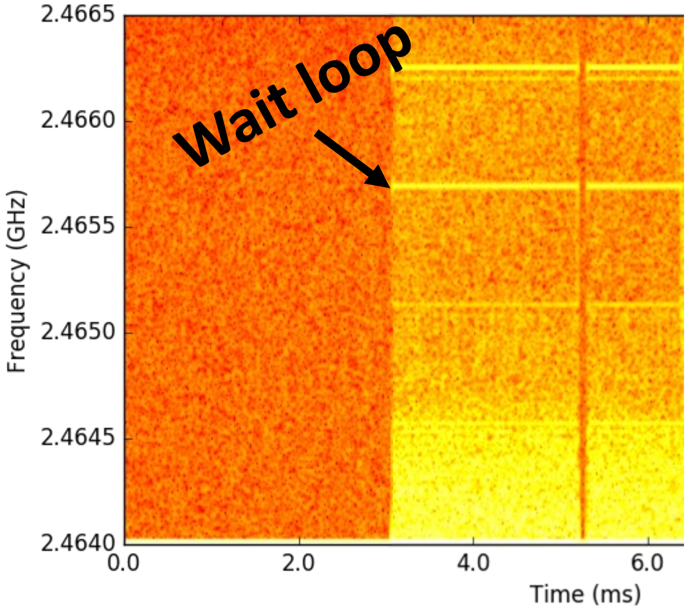
Screaming Channels [1] in Action

Antenna + SDR RX



Cortex-M4
+ BT TX

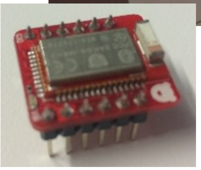
Radio Off **Radio TX**



Noise **Packet**

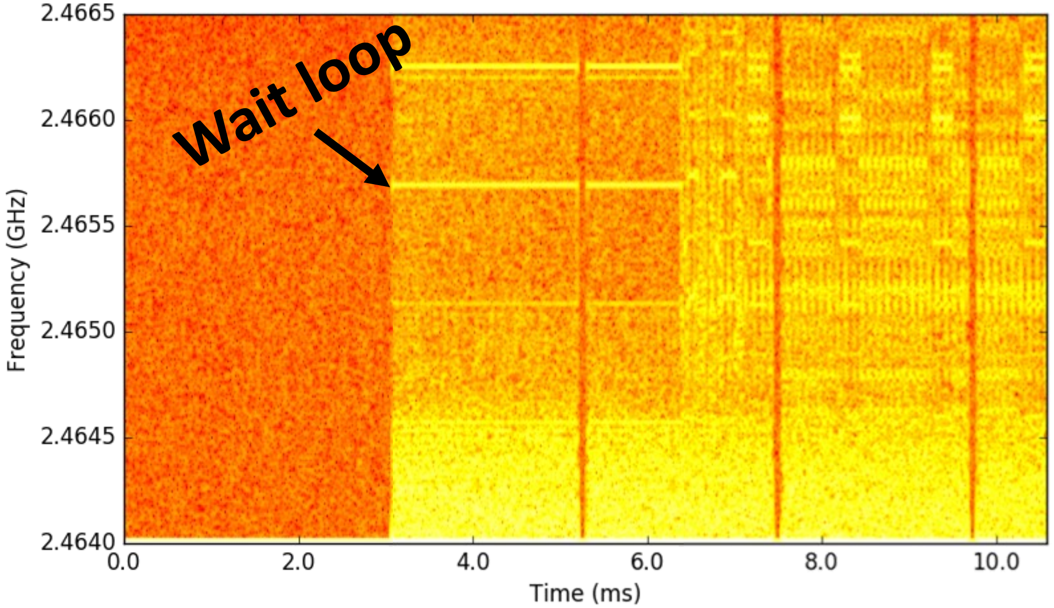
Screaming Channels [1] in Action

Antenna + SDR RX



Cortex-M4
+ BT TX

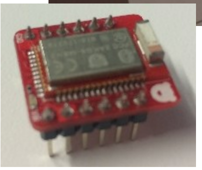
Radio Off Radio TX AES On



Noise Packet

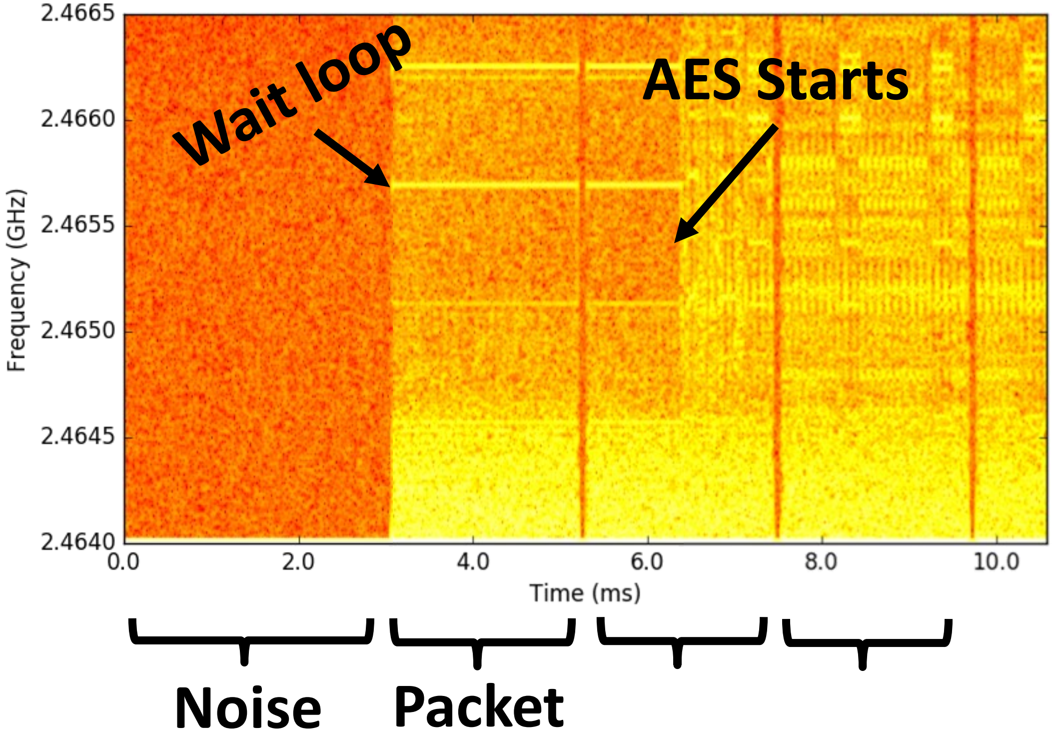
Screaming Channels [1] in Action

Antenna + SDR RX



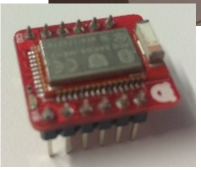
Cortex-M4
+ BT TX

Radio Off **Radio TX** **AES On**



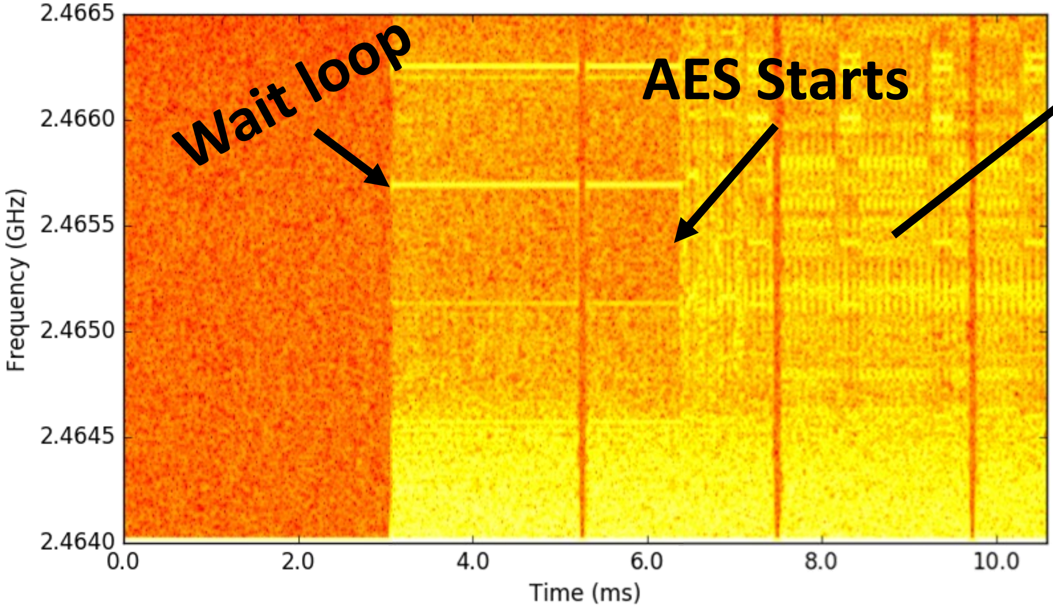
Screaming Channels [1] in Action

Antenna + SDR RX

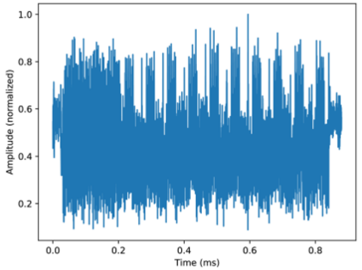


Cortex-M4
+ BT TX

Radio Off **Radio TX** **AES On**

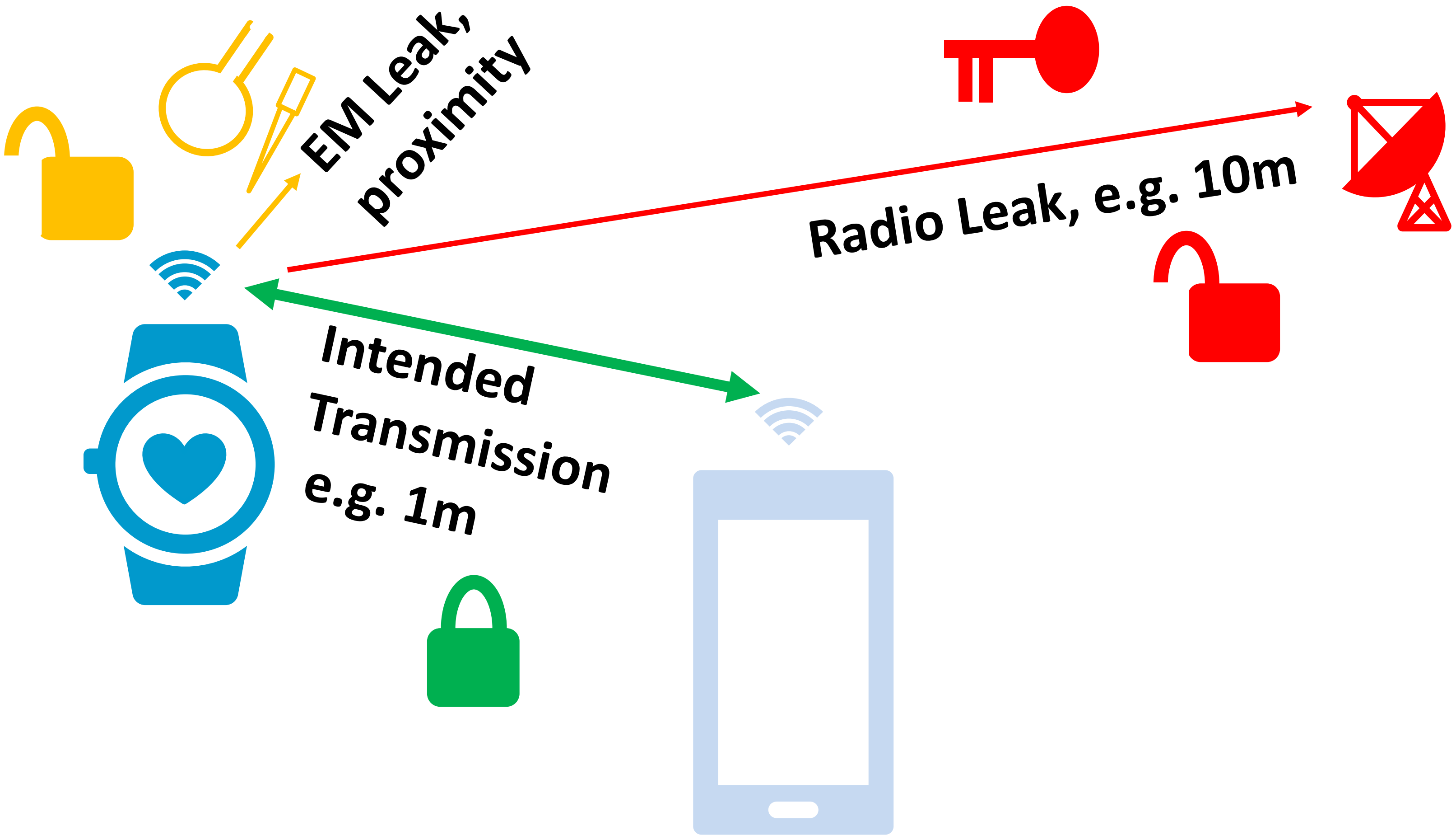


Noise **Packet**



Time domain

A New Threat [1]



The "Screaming Channels" Leak Vector

Idea, Root Cause, First Attack

Intuition and root cause

10m in anechoic chamber

Countermeasures

The "Screaming Channels" Leak Vector

Idea, Root Cause, First Attack
Intuition and root cause
10m in anechoic chamber
Countermeasures

CCS 2018 [1] & BHUSA18 [2]
Camurati, Poeplau, Muench, Hayes, Francillon

The "Screaming Channels" Leak Vector

Idea, Root Cause, First Attack

Intuition and root cause

10m in anechoic chamber

Countermeasures

CCS 2018 [1] & BHUSA18 [2]

Camurati, Poeplau, Muench, Hayes, Francillon

Systematic Analysis

Data/leak coexistence

Distortion, profile reuse, etc.

Improved Attacks

Realistic environment up to 15m

Google Eddystone Beacons

The "Screaming Channels" Leak Vector

Idea, Root Cause, First Attack
Intuition and root cause
10m in anechoic chamber
Countermeasures

CCS 2018 [1] & BHUSA18 [2]
Camurati, Poeplau, Muench, Hayes, Francillon

Systematic Analysis
Data/leak coexistence
Distortion, profile reuse, etc.

Improved Attacks
Realistic environment up to 15m
Google Eddystone Beacons

TCHES 2020
Camurati, Francillon, Standaert

Some Other Interesting Cases

“LeakyNoise”
CPU to ADC side channel in mixed-signal chips
CHES2019 [14]

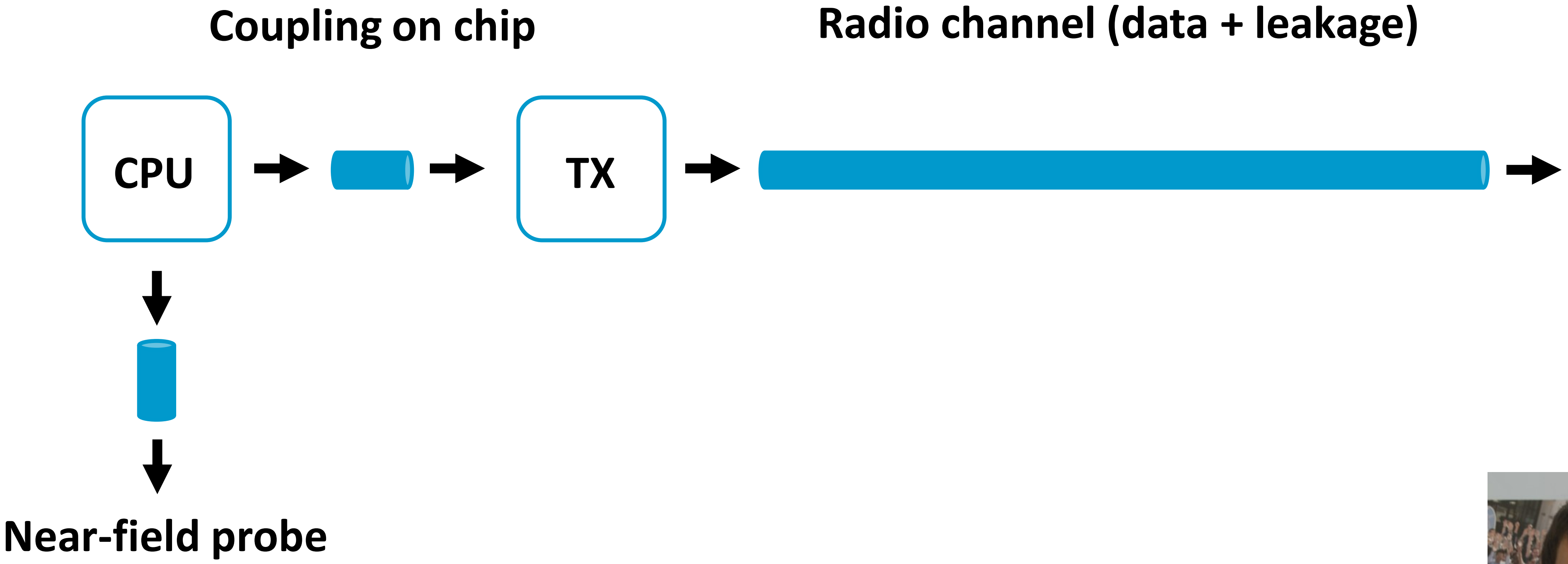
Second-Order Soft-TEMPEST
Soft-TEMPEST + (un)intentional cascaded effects
EMC Europe 2018 [15]
AP-RASC 2019 [16]

Let us answer some open questions about Screaming Channels

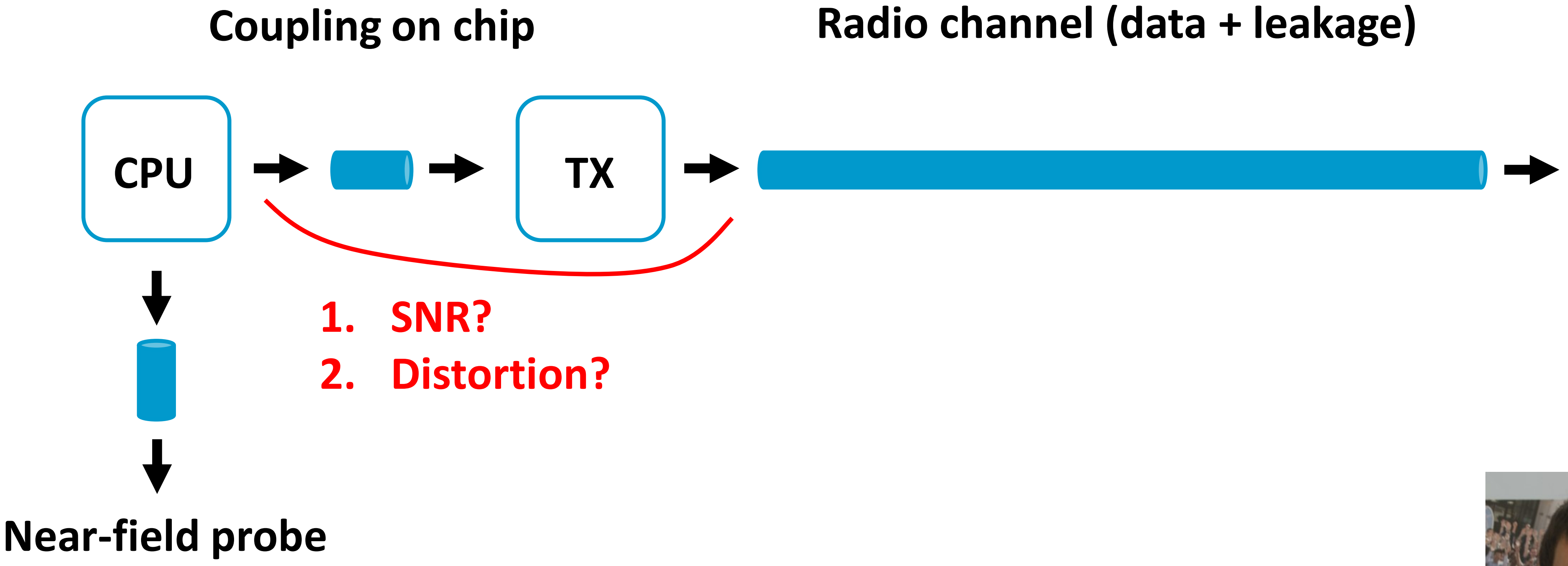
What is the difference with conventional leakages?

1/4

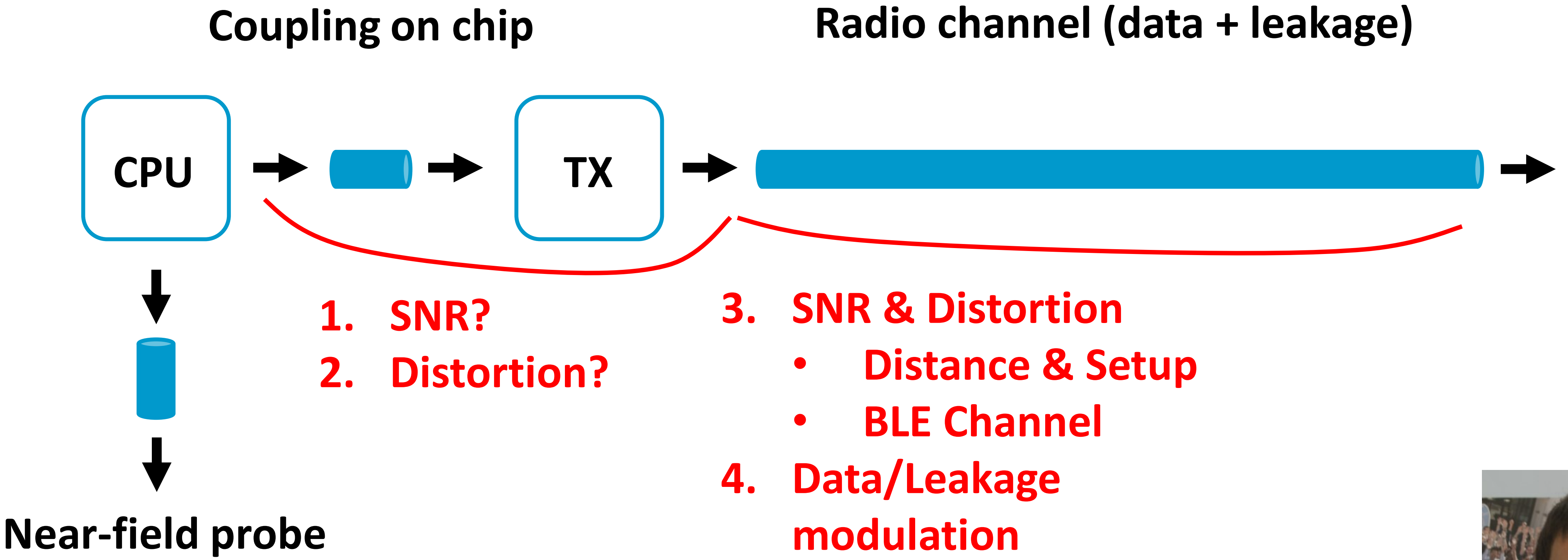
Intuitively



Intuitively



Intuitively



1. SNR?
2. Distortion?

3. SNR & Distortion
   - Distance & Setup
   - BLE Channel
4. Data/Leakage modulation
5. Discrete packets
6. Frequency hopping

Necessary Steps Before We Can Start

1. Extract traces (in the specific case of our BLE device)
    1. Data (GFSK) and leakage (AM) are orthogonal
    2. Trigger on a peculiar frequency
    3. Fix the channel (we will consider hopping later)
    4. Time diversity to deal with deep fade between packets

Necessary Steps Before We Can Start

1. Extract traces (in the specific case of our BLE device)
    1. Data (GFSK) and leakage (AM) are orthogonal
    2. Trigger on a peculiar frequency
    3. Fix the channel (we will consider hopping later)
    4. Time diversity to deal with deep fade between packets
2. Normalize
    1. Z-score normalization inspired by [3,4,5,6]
    2. Per-trace normalization removes the effect of the channel!

Necessary Steps Before We Can Start

1. Extract traces (in the specific case of our BLE device)
    1. Data (GFSK) and leakage (AM) are orthogonal
    2. Trigger on a peculiar frequency
    3. Fix the channel (we will consider hopping later)
    4. Time diversity to deal with deep fade between packets
2. Normalize
    1. Z-score normalization inspired by [3,4,5,6]
    2. Per-trace normalization removes the effect of the channel!

$$y(t) = Gx(t)$$

$$y' = \frac{y - avg(y)}{std(y)} = \frac{Gx - Gavg(x)}{Gstd(x)} = x'$$

Understanding the Leakage

Leakage variable y = SBox(p xor k)

Leakage model m(y) = HW[y]

Leakage l(y)

Understanding the Leakage

Leakage variable **y** = SBox(p xor k)

Leakage model **m(y)** = ~~HW[y]~~ model(y) **Estimate (nonlinear) leakage model for each y, using the profiling set**

Leakage **l(y)**

Understanding the Leakage

Leakage variable y = SBox(p xor k)

Leakage model m(y) = ~~HW[y]~~ model(y)

Estimate (nonlinear) leakage model for each y, using the profiling set

Leakage l(y)

Estimate the linear correlation between m(y) and l(y) on test set

Understanding the Leakage

Leakage variable y = SBox(p xor k)

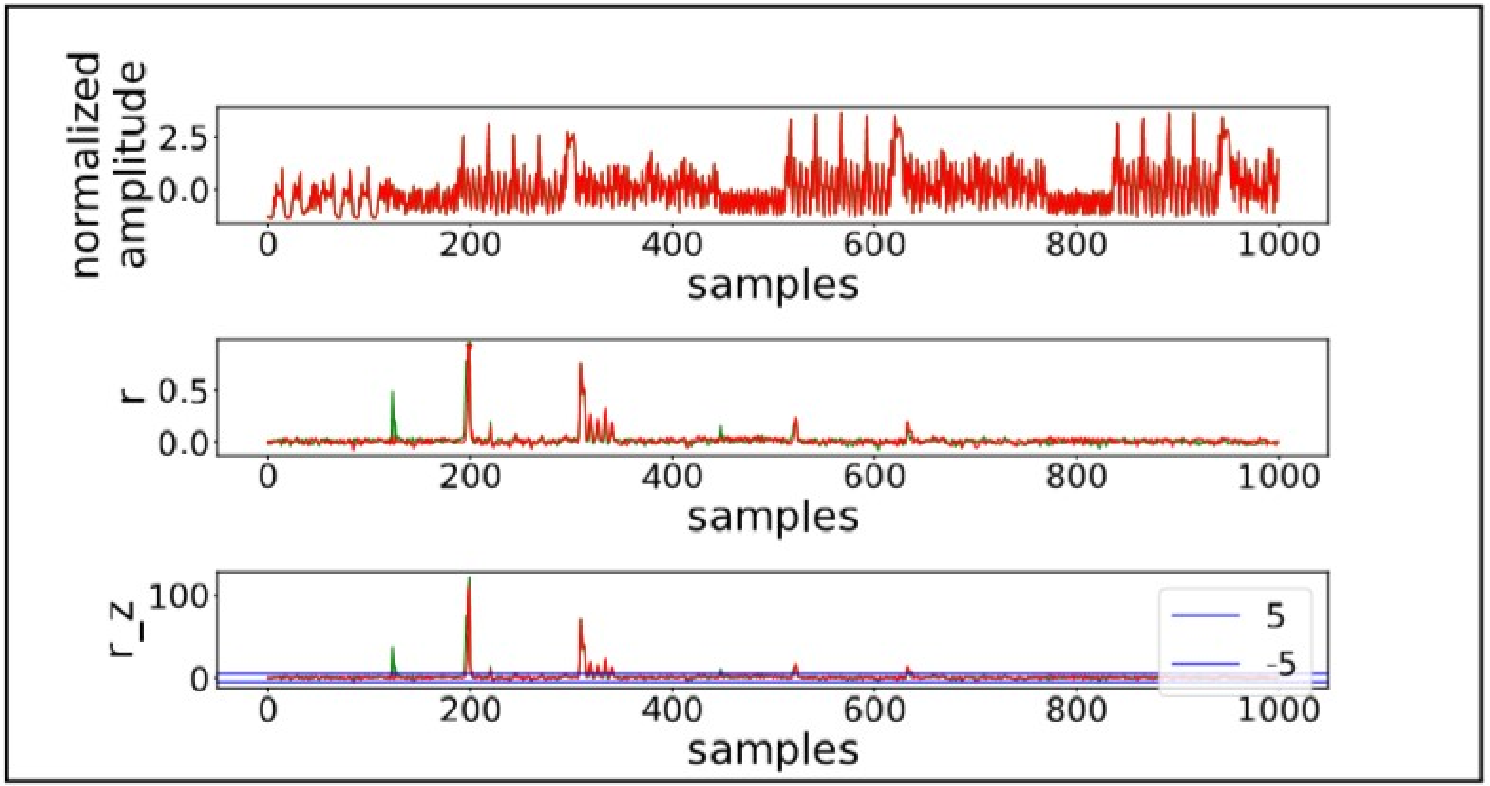
Leakage model m(y) = ~~HW[y]~~ model(y) **Estimate (nonlinear) leakage model for each y, using the profiling set**

Leakage l(y)

Estimate the linear correlation between m(y) and l(y) on test set

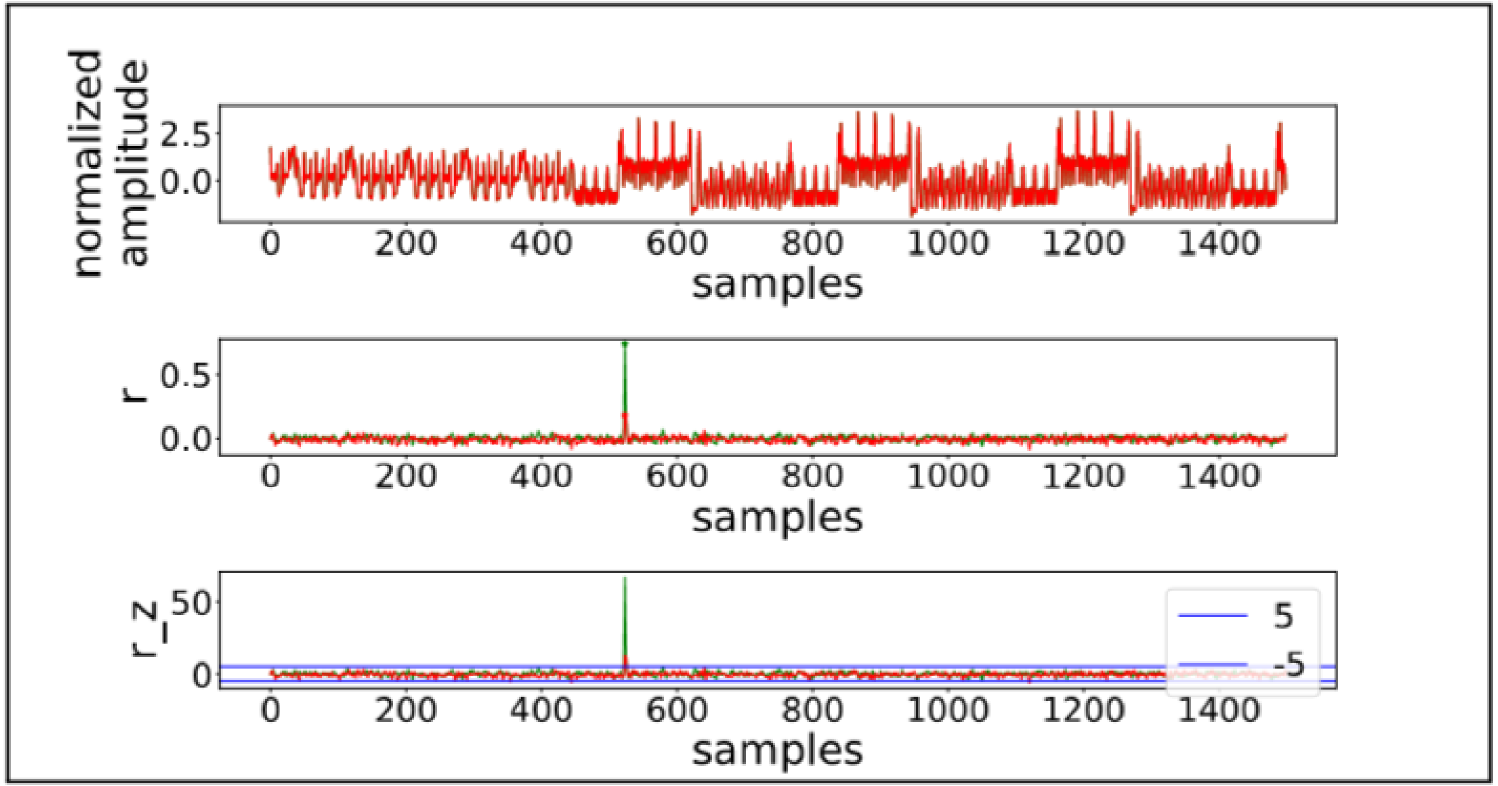
This is the r-test [7]

Understanding the Leakage

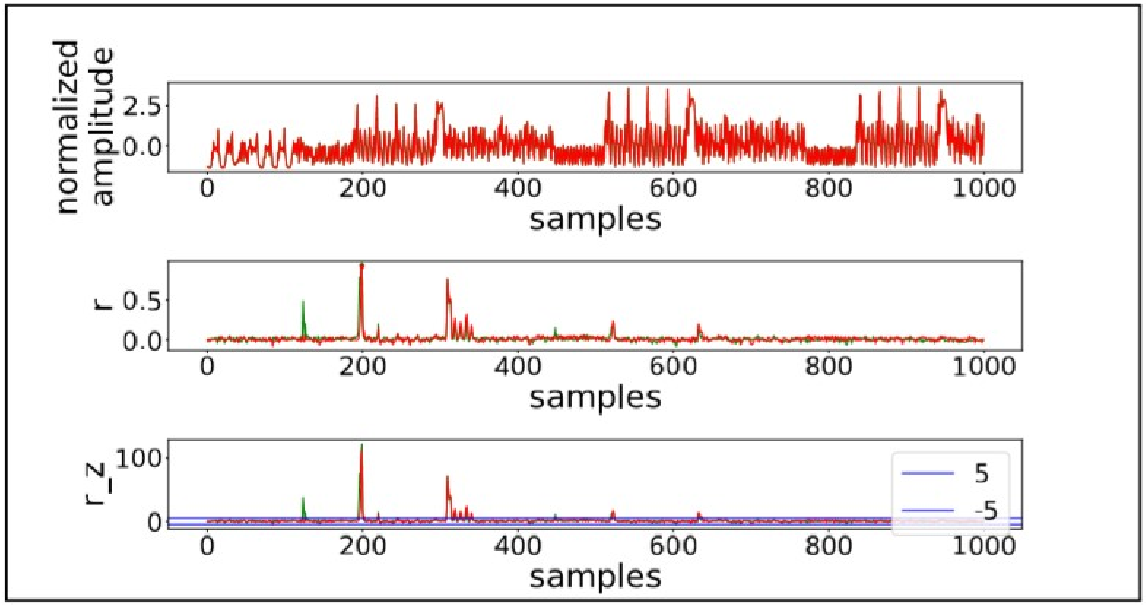


(a) ρ-test with $p \oplus k$ (green) and $HW(Sbox(p \oplus k))$

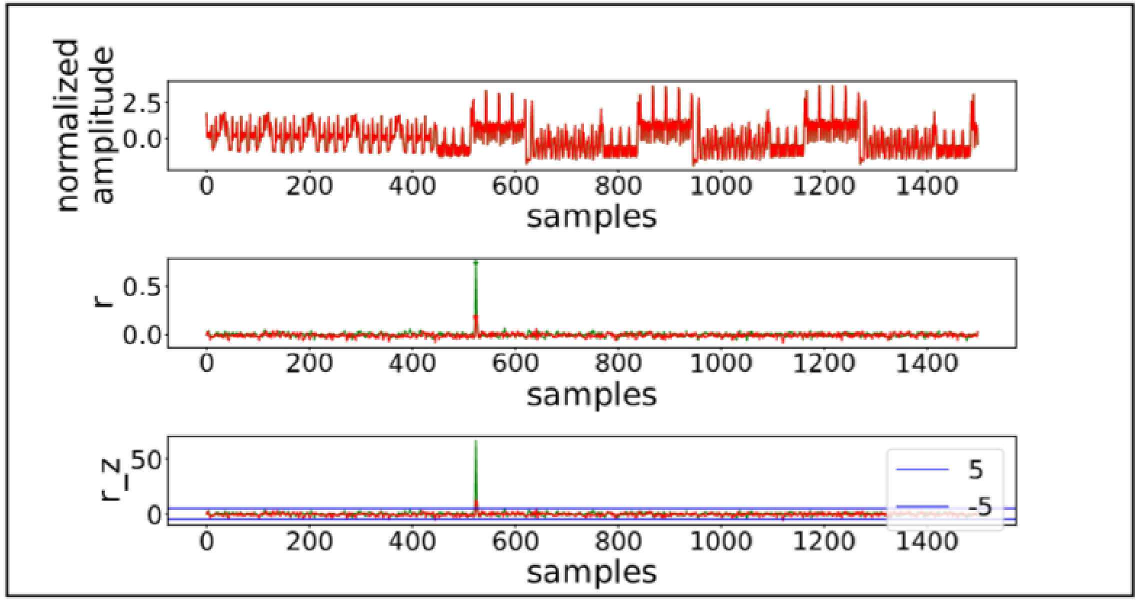
Understanding the Leakage



(b) Screaming 10 cm: ρ-test with $p \oplus k$ (green) and $HW(Sbox(p \oplus k))$ (red)



(a) ρ-test with $p \oplus k$ (green) and $HW(Sbox(p \oplus k))$



(b) Screaming 10 cm: ρ-test with $p \oplus k$ (green) and $HW(Sbox(p \oplus k))$ (red)

Results for Screaming vs. Conventional

- **Less POIs**
- **Slightly lower but still high correlation**
- **HW is not a good model**

SNR is comparable
But the leakage is distorted

Understanding the Leakage

Leakage variable y = SBox(p xor k)

Leakage model m(y) = HW[y]

Leakage l(y)

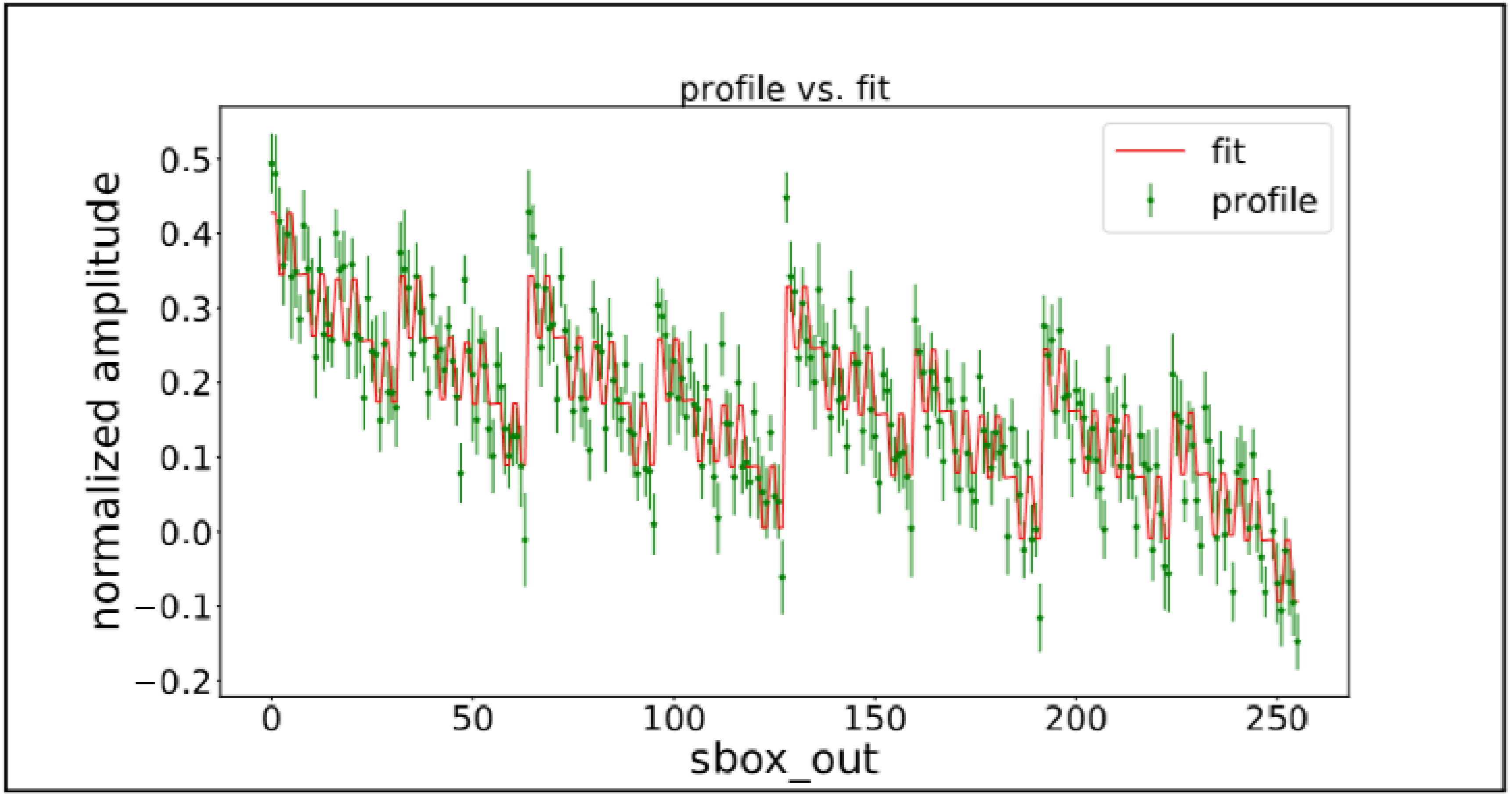
Understanding the Leakage

Leakage variable y = SBox(p xor k)

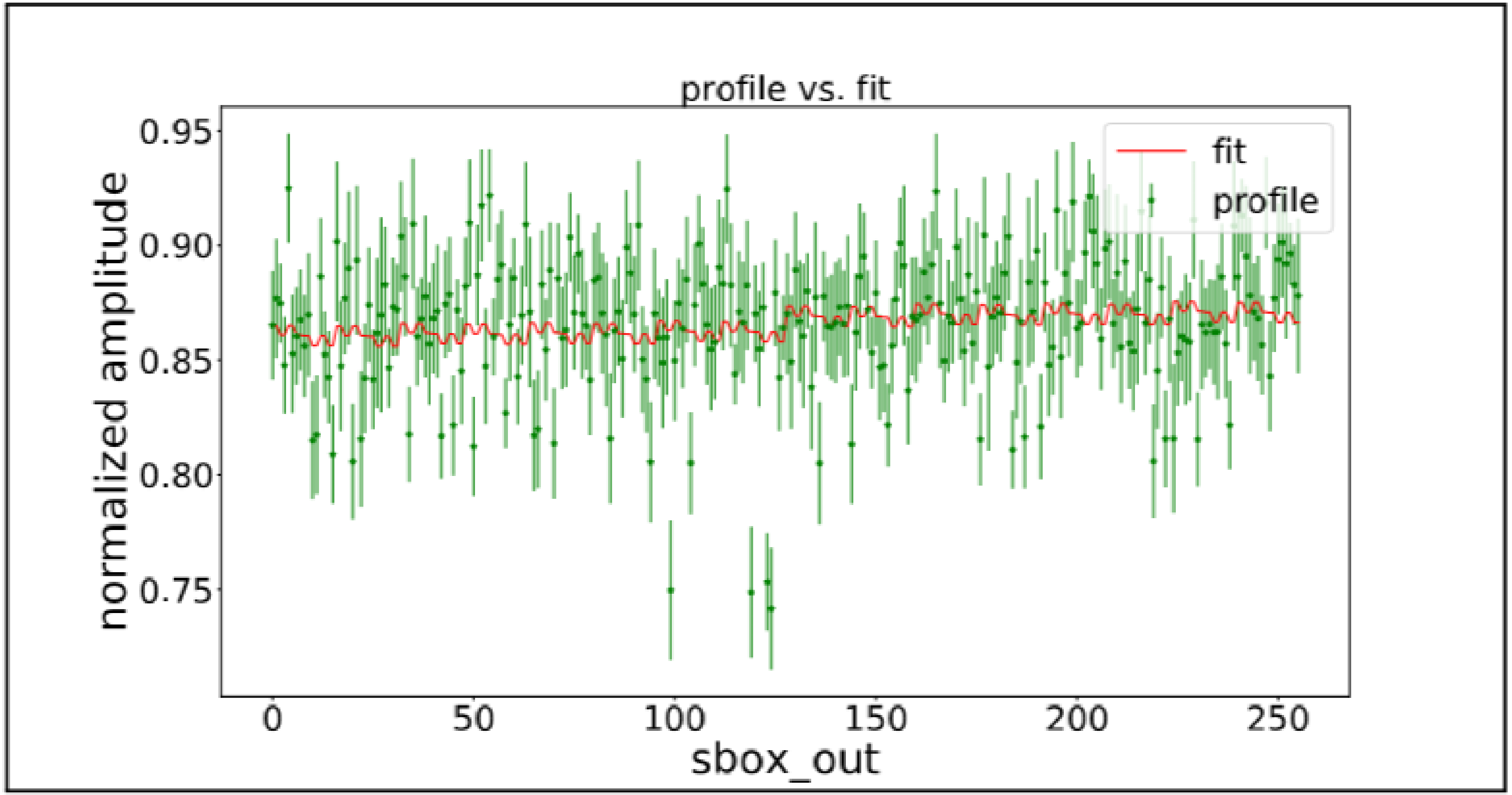
Leakage model m(y) = ~~HW~~[y] **Linear combination of the bits of y**

Leakage l(y)

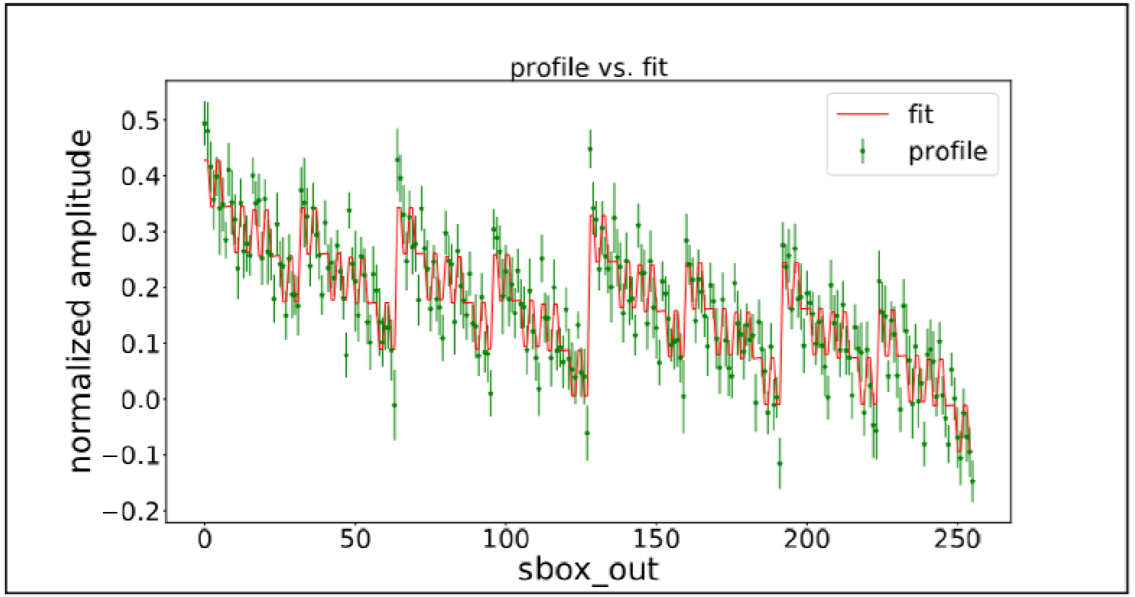
Estimate a linear model of the bits of y using linear regression [7]



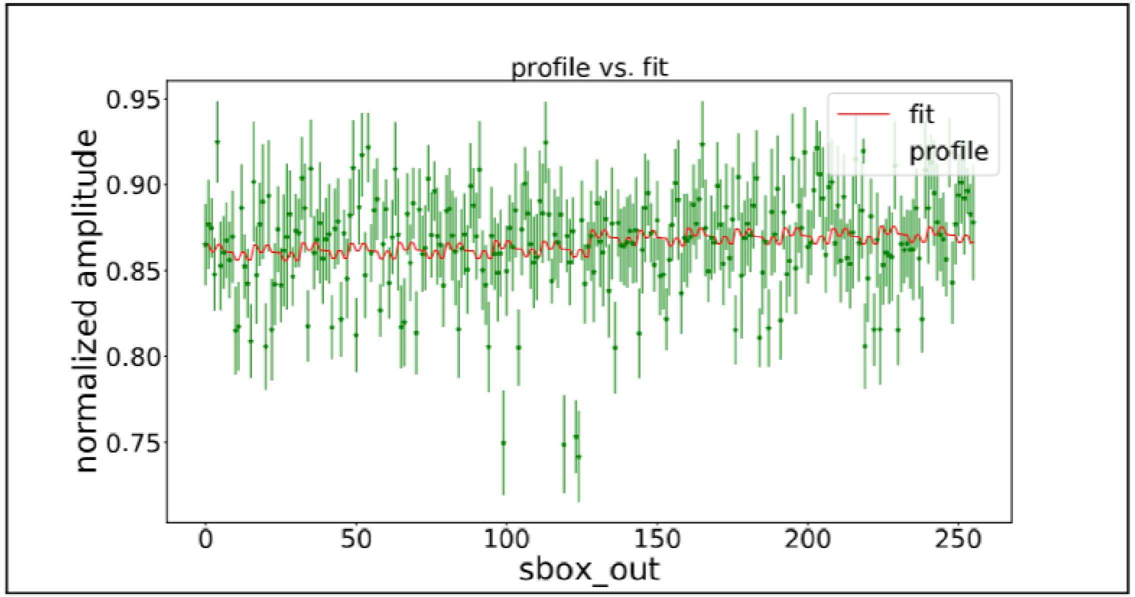
(a) Conventional



(b) Screaming at 10 cm



(a) Conventional



(b) Screaming at 10 cm

Results for Screaming vs. Conventional

- **Confirm leakage from Sbox output**
- **Linear model is good for conventional traces**
- **Bad for screaming traces** **The leakage model is nonlinear**

Understanding the Leakage

Leakage variable y

Leakage model m(y)

Leakage l(y)

Templates [9] can capture a second order relation between m(y) and l(y)

Understanding the Leakage

Leakage variable y

Leakage model m(y)

Leakage l(y)

Templates [9] can capture a second order relation between m(y) and l(y)

Results for Screaming vs. Conventional

- **Templates attacks are not considerably better than profiled correlation attacks**

First-order leakage (for our sample size)

Conclusion

1. **Comparable SNR, distorted leakage model**
2. **Nonlinear leakage model**
3. **First order leakage**

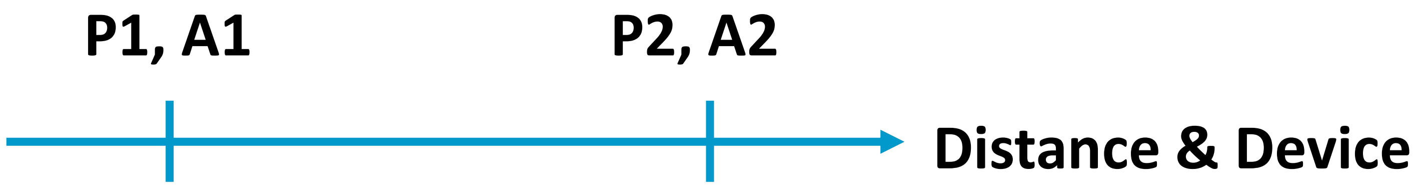
Profiled Correlation Attacks

Can we reuse the profiles?

2/4

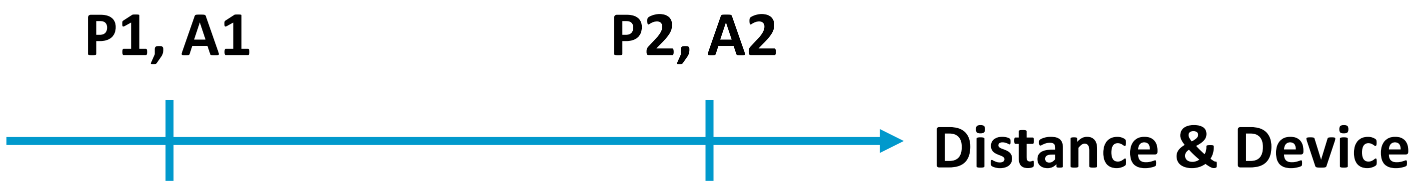
How To Compare Profiles

#Traces for key recovery [10]
Given profile P and attack traces A



How To Compare Profiles

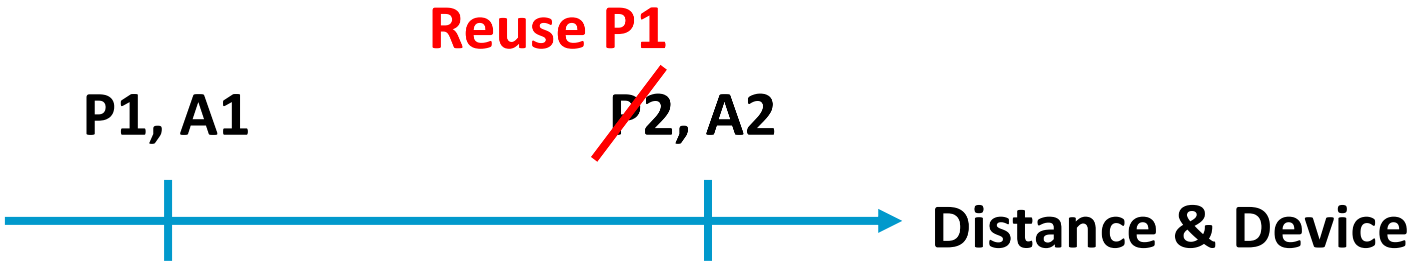
#Traces for key recovery [10]
Given profile P and attack traces A



$$\mathbf{N11} \propto r^{-2}(P1, A1) \qquad \mathbf{N22} \propto r^{-2}(P2, A2)$$

How To Compare Profiles

#Traces for key recovery [10]
Given profile P and attack traces A

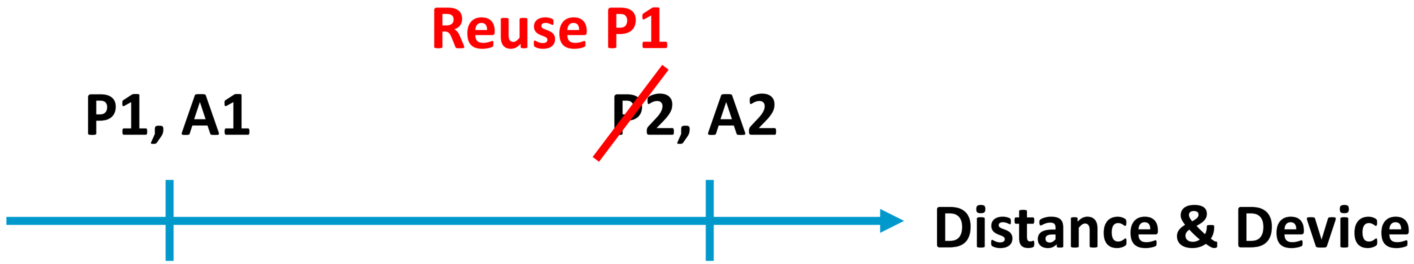


$$\mathbf{N11} \propto \boldsymbol{r^{-2}(P1, A1)} \qquad \mathbf{N22} \propto \boldsymbol{r^{-2}(P2, A2)}$$

How To Compare Profiles

#Traces for key recovery [10]

Given profile P and attack traces A



$$\mathbf{N11} \propto r^{-2}(P1, A1) \qquad \cancel{\mathbf{N22} \propto r^{-2}(P2, A2)}$$

$$\mathbf{N12} \propto r^{-2}(P1, A2)$$

$$r(P1, A2) = r(P2, A2)\,r(P1, P2)$$

The higher the better

Distance, Setup, Channel Frequency, Instance, Time

Distance

- **Quadratic power loss, but we can amplify**
- **Normalization cancels the multiplicative channel gain**
- **No extra distortion (different from conventional [11])**

Distance, Setup, Channel Frequency, Instance, Time

Distance

- Quadratic power loss, but we can amplify
- Normalization cancels the multiplicative channel gain
- No extra distortion (different from conventional [11])

Environment (noise) and setup

- Bigger role than distance, but we can improve the setup
- Some connections are better

Distance, Setup, Channel Frequency, Instance, Time

Distance

- Quadratic power loss, but we can amplify
- Normalization cancels the multiplicative channel gain
- No extra distortion (different from conventional [11])

Environment (noise) and setup

- Bigger role than distance, but we can improve the setup
- Some connections are better

Device instance

- No significant impact, per-trace normalization helps

Distance, Setup, Channel Frequency, Instance, Time

Distance

- **Quadratic power loss, but we can amplify**
- **Normalization cancels the multiplicative channel gain**
- **No extra distortion (different from conventional [11])**

Environment (noise) and setup

- **Bigger role than distance, but we can improve the setup**
- **Some connections are better**

Device instance

- **No significant impact, per-trace normalization helps**

Big Advantage

- **Profile in good conditions, attack another instance in harsh conditions**

Example: Distance

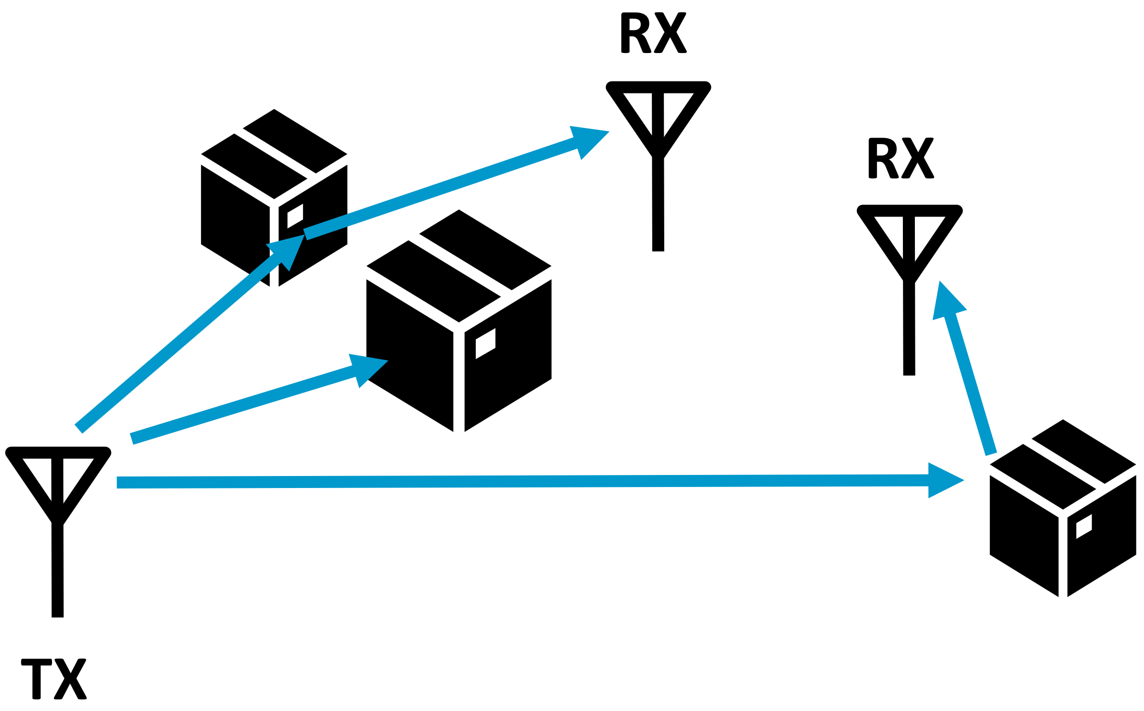
	d (m)	environment	antenna	$\hat{r}(P_i,P_2)$, -log10(p)	$max \rho, r_z$
P_2	0.10	home	standard	1.00, inf	0.79, 75.72
P_3	0.20	home	standard	0.96, 142.77	0.77, 72.30
P_4	1.00	office	directional	0.40, 10.32	0.41, 30.66
P_5	5.00	anechoic	directional	0.96, 139.51	0.85, 89.84
P_6	10.00	anechoic	directional	0.92, 107.80	0.77, 71.71

High correlation between profiles

High correlation at each distance

Can we attack more challenging targets?
3/4

Attacks with obstacles and spatial diversity



Spatial Diversity

Different paths

Uncorrelated noise

Combine with Maximal Ratio

Attack

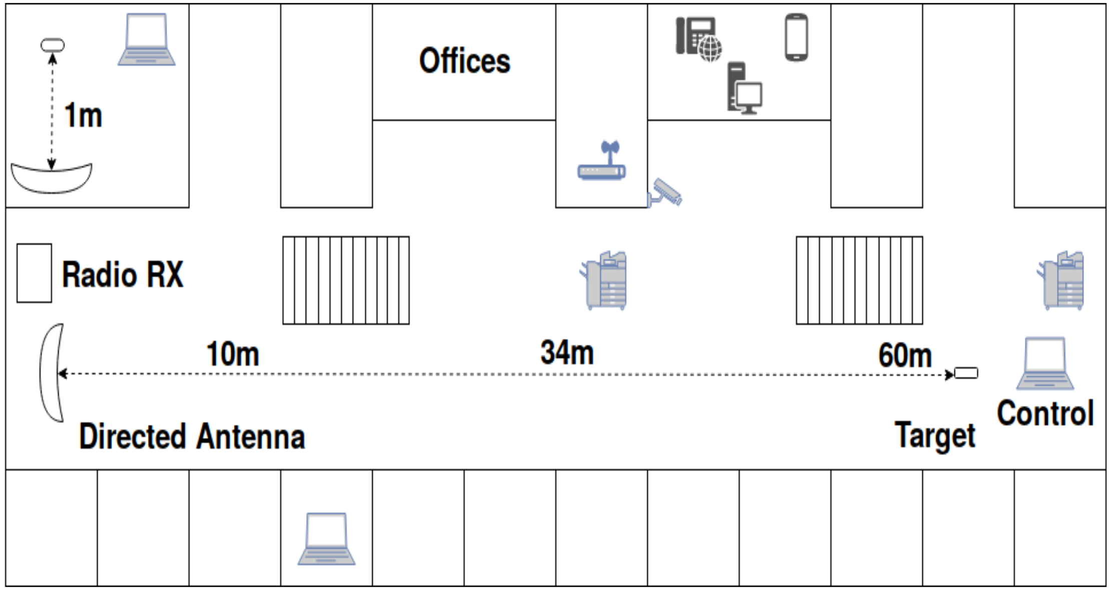
55cm in home environment

37k x 500 profiling traces

1990 x 500 attack traces

Rank 2^26

Attacks in an office environment



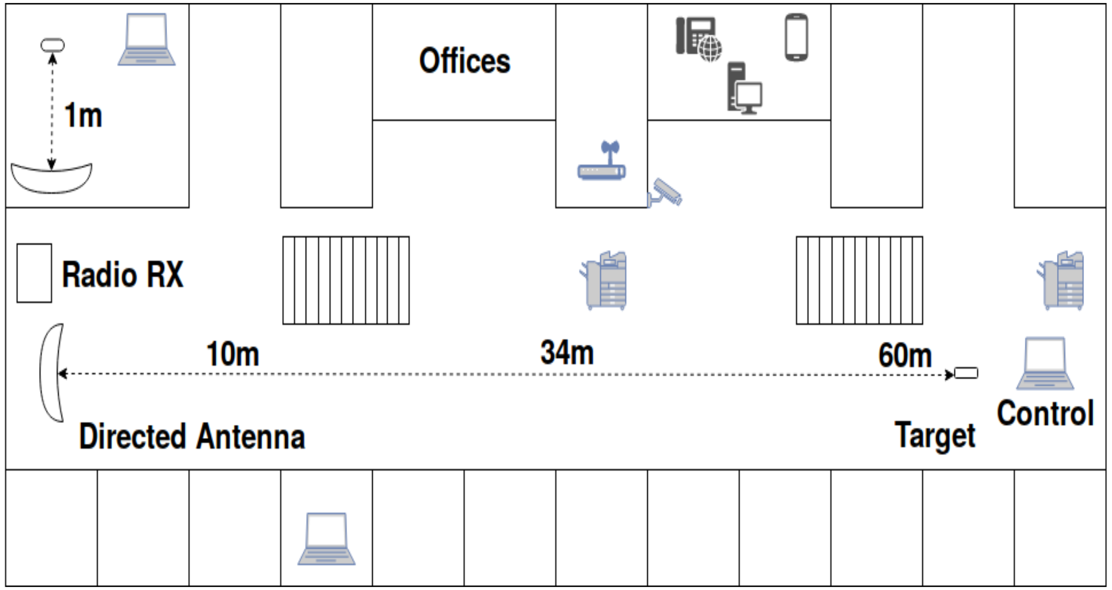
Simple Profiling

Connection via cable
(10k x 500 traces)

Complex Attack

Different instance and time
10m (1.5k x 1000 traces, 2^28)
15m (5k x 1000 traces, 2^23, hard)

Attacks in an office environment



Simple Profiling

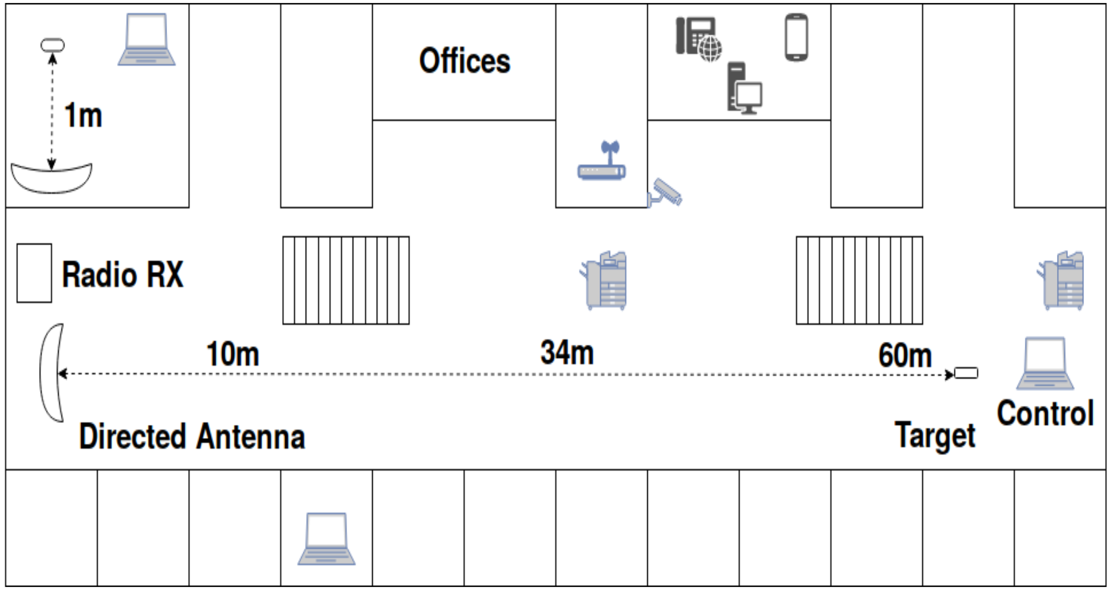
Connection via cable
(10k x 500 traces)

Complex Attack

Different instance and time
10m (1.5k x 1000 traces, 2^28)
15m (5k x 1000 traces, 2^23, hard)

Setup tuning becomes critical

Attacks in an office environment



Simple Profiling

Connection via cable
(10k x 500 traces)

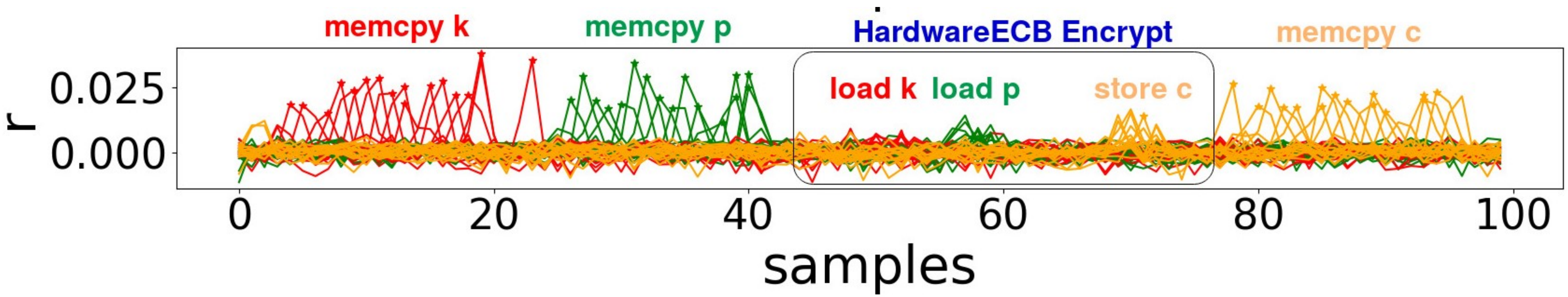
Complex Attack

Different instance and time
10m (1.5k x 1000 traces, 2^28)
15m (5k x 1000 traces, 2^23, hard)

Setup tuning becomes critical

34m (2k x 1000 traces, t-test only)
60m (extraction only)

What about the hardware AES block?



Simple Setup

10cm in office

USRP N210

350k x 100 traces

Leaks from Memory Transfers

Firmware *memcpy* of p,c,k

Hardware DMA of p,c,k

No leak detected inside the AES

Attacks

Only SPA attack are possible

As of now we have not succeeded

Can we attack a real system?
4/4

What are Google Eddystone Beacons [12]?

What are Google Eddystone Beacons [12]?

UID identifier
URL e.g., www.museumshop.com
(e)TML (encrypted) telemetry
EID ephemeral id

What are Google Eddystone Beacons [12]?

UID identifier
URL e.g., www.museumshop.com
(e)TML (encrypted) telemetry
EID ephemeral id

Physical Web, Proximity Marketing, ...
Really used, though less popular now

What are Google Eddystone Beacons [12]?

UID identifier
URL e.g., www.museumshop.com
(e)TML (encrypted) telemetry
EID ephemeral id

Physical Web, Proximity Marketing, ...
Really used, though less popular now

Configuration
Authentication at GATT layer
Preshared key
AES128

What are Google Eddystone Beacons [12]?

UID identifier
URL e.g., www.museumshop.com
(e)TML (encrypted) telemetry
EID ephemeral id

Physical Web,
Proximity
Marketing, ...
Really used, though less popular now

Security & Privacy
Considered during design of the protocol

Configuration
Authentication at GATT layer
Preshared key
AES128

Triggering AES encryptions with known plaintext

Beacon

Pre-shared key K

Owner/
Attacker

Read Unlock Characteristic

P = Random()

P

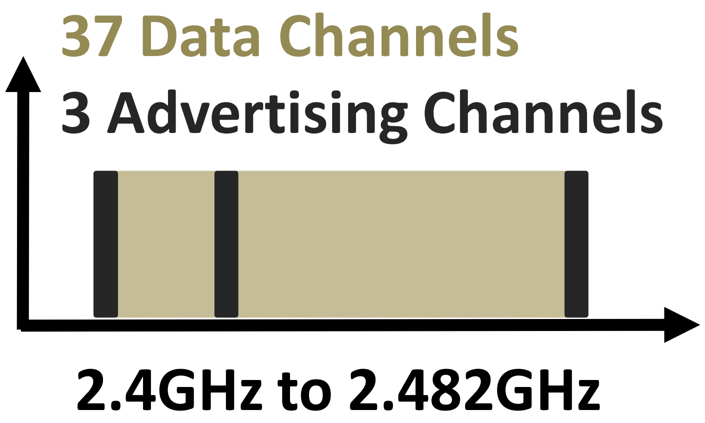
CB = AES128(P,K)

CO = AES128(P,K)

Write Unlock Characteristic

Unlocked = (CB == CO)

Reducing the problem of frequency hopping



Frequency Hopping

A form of spread spectrum

Channel changes randomly

Hard to follow (sequence, speed, bandwidth)

Reducing the problem of frequency hopping

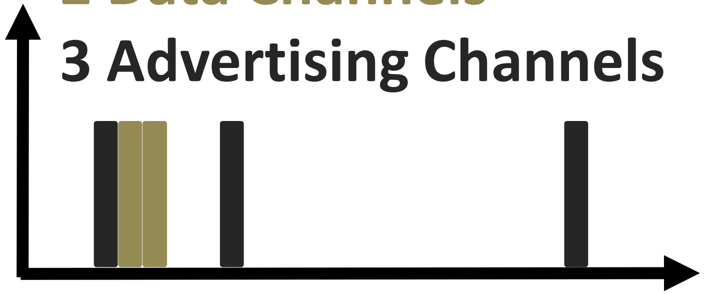
37 Data Channels

3 Advertising Channels

2.4GHz to 2.482GHz

2 Data Channels

3 Advertising Channels



2.4GHz to 2.482GHz

Frequency Hopping

A form of spread spectrum

Channel changes randomly

Hard to follow (sequence, speed, bandwidth)

Channel Map

E.g., *hcitool cmd 0x08 0x0014 0x0000000003*

The attacker can block

up to 35 channels

The complete attack

Google Bughunter Program
Honorable Mention

Threat Model

Beacon with no physical access

- **Not protected from EM/Power side channels**
- **Always connectable**

The complete attack

Google Bughunter Program
Honorable Mention

Threat Model

Beacon with no physical access

- **Not protected from EM/Power side channels**
- **Always connectable**

Realistic Demo

Unmodified Nordic SDK demo [13]

- **Optimized code (O3)**
- **Hopping Enabled (reduced with channel map)**
- **TinyAES software (hardware in later versions)**

The complete attack

Google Bughunter Program
Honorable Mention

Threat Model

Beacon with no physical access

- **Not protected from EM/Power side channels**
- **Always connectable**

Realistic Demo

Unmodified Nordic SDK demo [13]

- **Optimized code (O3)**
- **Hopping Enabled (reduced with channel map)**
- **TinyAES software (hardware in later versions)**

Proof-of-Concept Attack (connection via cable on PCA10040)

70k x 1 profiling traces, 33k x 1 attack traces, rank 2^30

Countermeasures?

Countermeasures

Resource constraint devices:
Cost, power, time to market, etc.

Countermeasures

Resource constraint devices:
Cost, power, time to market, etc.

Classic HW/SW:
Masking, noise, key refresh, limit attempts, use hardware block, ...

Countermeasures

Resource constraint devices:
Cost, power, time to market, etc.

Classic HW/SW:
Masking, noise, key refresh, limit attempts, use hardware block, ...

Specific (SW):
Radio off during sensitive computations
Force use of HW encryption (for now)

Countermeasures

Resource constraint devices:
Cost, power, time to market, etc.

Classic HW/SW:
Masking, noise, key refresh, limit attempts, use hardware block, ...

Specific (SW):
Radio off during sensitive computations
Force use of HW encryption (for now)

Specific (HW):
Consider impact of coupling on security during design and test

Conclusion

Conclusion

General Problem: **Radios and Side Channels**
New threat point: **Digital activity visible from a large distance**

Conclusion

General Problem: Radios and Side Channels
New threat point: Digital activity visible from a large distance

$\neq$

Peculiar: Not a conventional side channel vector
Easier: Amplified leak, large distance, simple and cheap setup
Harder: Distortion, channel noise, data/leak coexistence

Conclusion

General Problem: Radios and Side Channels
New threat point: Digital activity visible from a large distance

Peculiar: Not a conventional side channel vector
Easier: Amplified leak, large distance, simple and cheap setup
Harder: Distortion, channel noise, data/leak coexistence

Threat: More and more realistic attacks
Potential threat: More devices or new devices are vulnerable
Countermeasures: Clever, specific countermeasures

Conclusion

General Problem: Radios and Side Channels
New threat point: Digital activity visible from a large distance

Peculiar: Not a conventional side channel vector
Easier: Amplified leak, large distance, simple and cheap setup
Harder: Distortion, channel noise, data/leak coexistence

Threat: More and more realistic attacks
Potential threat: More devices or new devices are vulnerable
Countermeasures: Clever, specific countermeasures

WiFi? Possible even if not orthogonal?
Hardware AES? Attack the memory transfers?

Open Source!

https://eurecom-s3.github.io/screaming_channels/

Code + Data + Instructions

Thank You!

Come to the live session for questions!

Or write me:

@GioCamurati
https://giocamurati.github.io
camurati@eurecom.fr

Acknowledgements

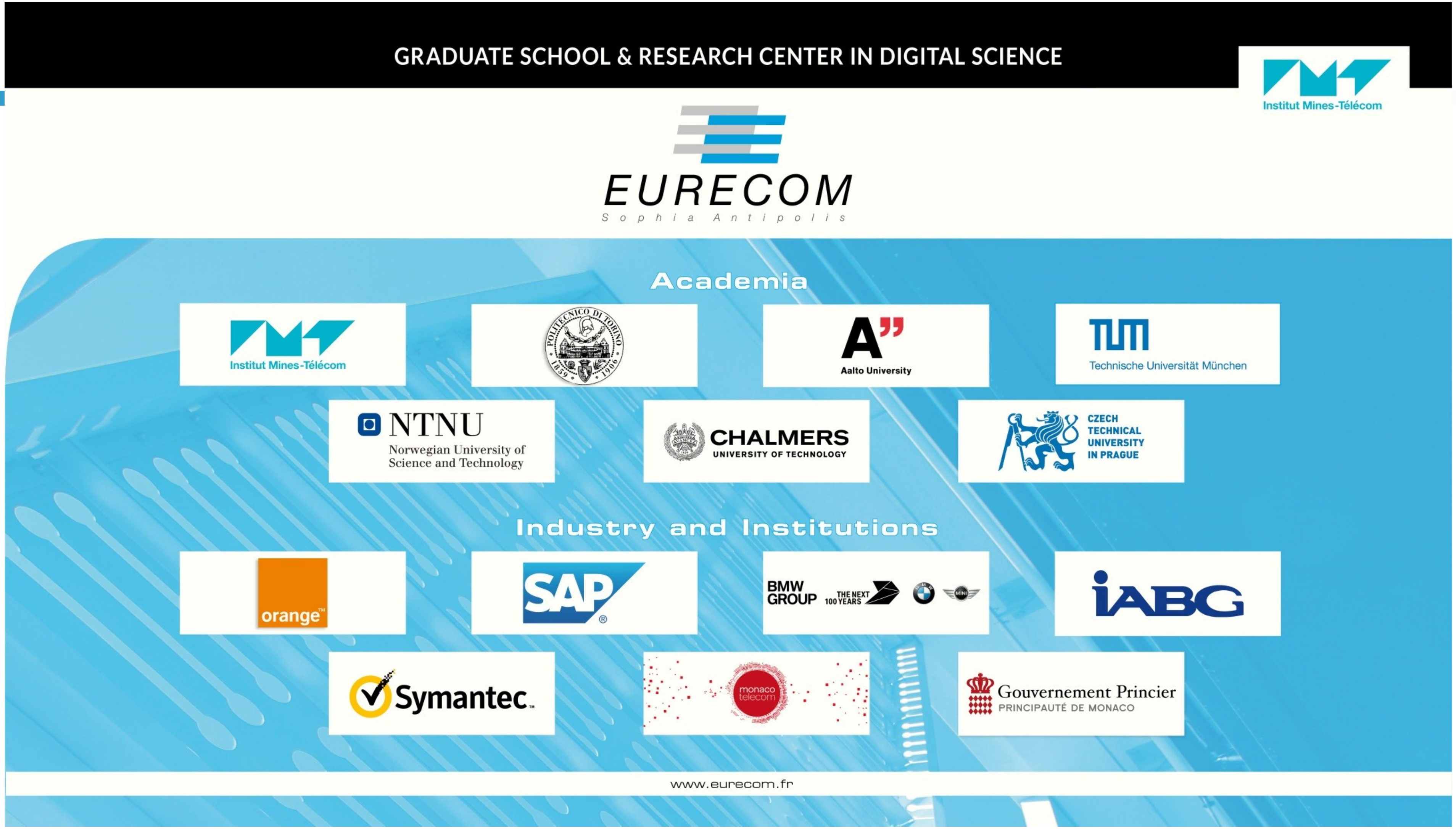
- The authors acknowledge the support of SeCiF project within the French-German Academy for the Industry of the future, as well as the support by the DAPCODS/IOTics ANR 2016 project (ANR-16-CE25-0015).
- We would like to thank the FIT R2lab team from Inria, Sophia Antipolis, for their help in using the R2lab testbed.

References

[1] Camurati et al., "Screaming Channels: When Electromagnetic Side Channels Meet Radio Transceivers." ACM CCS 2018.
[2] Camurati et al., "Screaming Channels: When Electromagnetic Side Channels Meet Radio Transceivers." Black Hat USA 2018.
[3] Hanley et al., "Empirical Evaluation of Multi-Device Profiling Side-Channel Attacks."
[4] Choudary and Kuhn, "Template Attacks on Different Devices."
[5] Montminy et al., "Improving Cross-Device Attacks Using Zero-Mean Unit-Variance Normalization."
[6] Elaabid and Guilley, "Portability of Templates."
[7] Durvaux and Standaert, "From Improved Leakage Detection to the Detection of Points of Interests in Leakage Traces."
[8] Schindler, Lemke, and Paar, "A Stochastic Model for Differential Side Channel Cryptanalysis."
[9] Chari, Rao, and Rohatgi, "Template Attacks."
[10] Standaert et al., "An Overview of Power Analysis Attacks Against Field Programmable Gate Arrays."
[11] Meynard et al., "Far Correlation-Based EMA with a Precharacterized Leakage Model."
[12] Google, Eddystone. https://github.com/google/eddystone
[13] Nordica Semiconductor, nRF5_SDK_v14.2.0. https://developer.nordicsemi.com/nRF5_SDK/nRF5_SDK_v14.x.x/nRF5_SDK_14.2.0_17b948a.zip
[14] Gnad et al., "LeakyNoise: New Side-Channel Attack Vectors in Mixed-Signal IoT Devices". CHES2019
[15] Cottais et al., "Second Order Soft-TEMPEST in RF Front-Ends: Design and Detection of Polyglot Modulations." EMC Europe 2018
[16] Esteves et al., "Second Order Soft Tempest: from Internal Cascaded Electromagnetic Interactions to Long Haul Covert ChannelsSecond Order Soft Tempest: from Internal Cascaded Electromagnetic Interactions to Long Haul Covert Channels." AP-RASC 2019

Third-Party Images

- "nRF51822 - Bluetooth LE SoC : weekend die-shot" - CC-BY– Modified with annotations. Original by zeptobars https://zeptobars.com/en/read/nRF51822-Bluetooth-LE-SoC-Cortex-M0


GRADUATE SCHOOL & RESEARCH CENTER IN DIGITAL SCIENCE
Institut Mines-Télécom
EURECOM
Sophia Antipolis
Academia
Institut Mines-Télécom
Aalto University
Technische Universität München
NTNU
Norwegian University of Science and Technology
CHALMERS
UNIVERSITY OF TECHNOLOGY
CZECH TECHNICAL UNIVERSITY IN PRAGUE
Industry and Institutions
orange
SAP
BMW GROUP
THE NEXT 100 YEARS
IABG
Symantec.
monaco telecom
Gouvernement Princier
PRINCIPAUTÉ DE MONACO
www.eurecom.fr