EURECOM
Sophia Antipolis

Screaming Channels

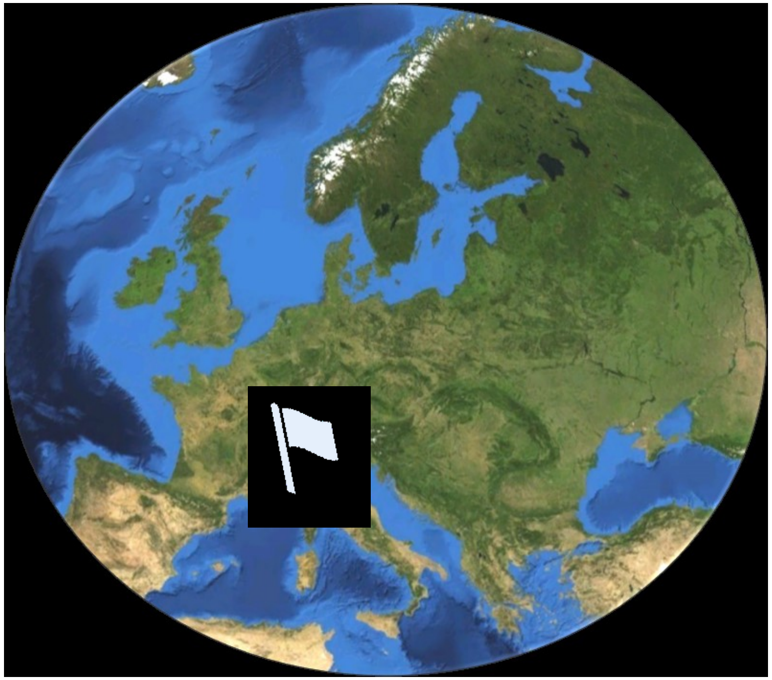
When Electromagnetic Side Channels Meet Radio Transceivers

Giovanni Camurati, Sebastian Poeplau, Marius Muench,
Tom Hayes, Aurélien Francillon

RESSI

15-05-2019

Who are we?



System and Software Security Group at EURECOM s3.eurecom.fr

I am a PhD student "on radio side channels"

Side Channels, The Idea

Theory

Secure lock is impossible to open

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Secure lock is impossible to open

Implementation

Different sound if we make a partial correct guess

Side Channels, The Idea

Theory

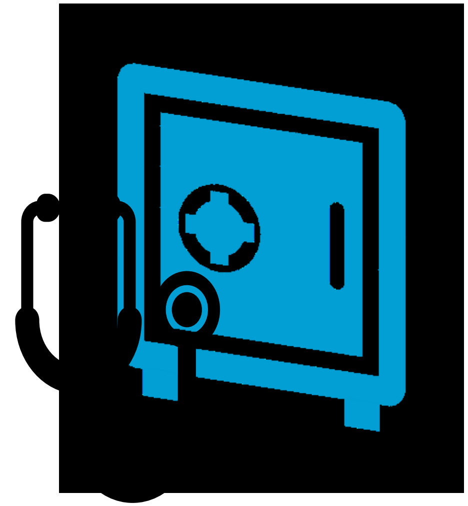
Secure lock is impossible to open

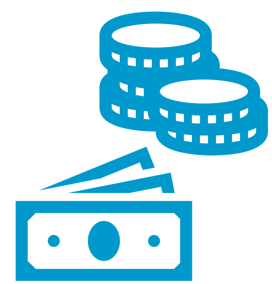
Implementation

Different sound if we make a partial correct guess

Attack

Open it with a few attempts





Embedded Devices and Side Channels

Secure systems:
E-Passport,
Smartcard, ...

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Crypto against stealing, cloning, tampering, …

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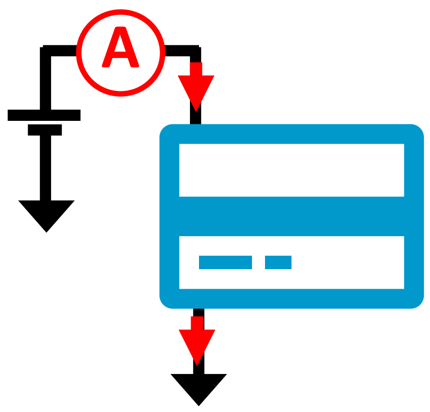
Generally protected against attacks which require physical access

Conventional Side Channels

Physical activity depends on logic data

Conventional Side Channels

Power (current)

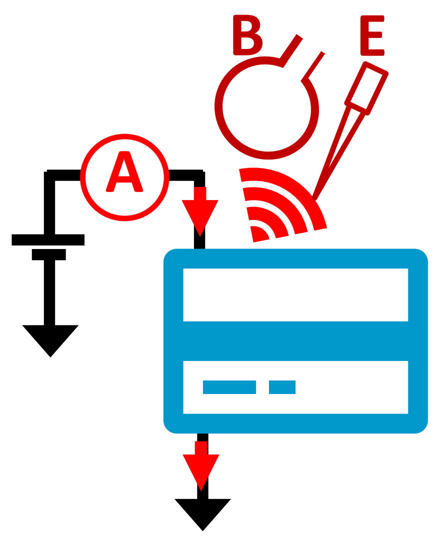


Physical activity depends on logic data

Conventional Side Channels

Direct EM

Power (current)



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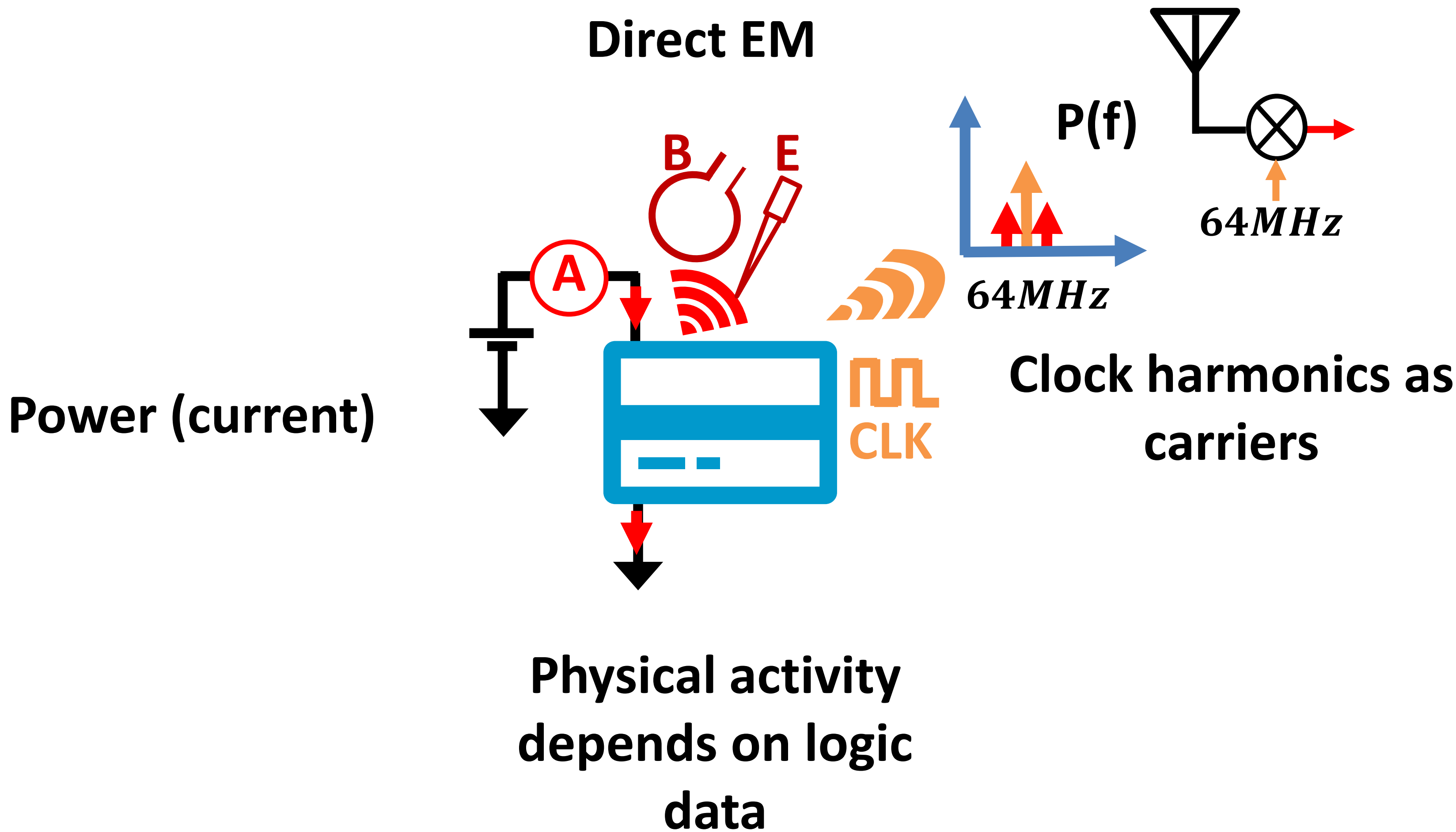
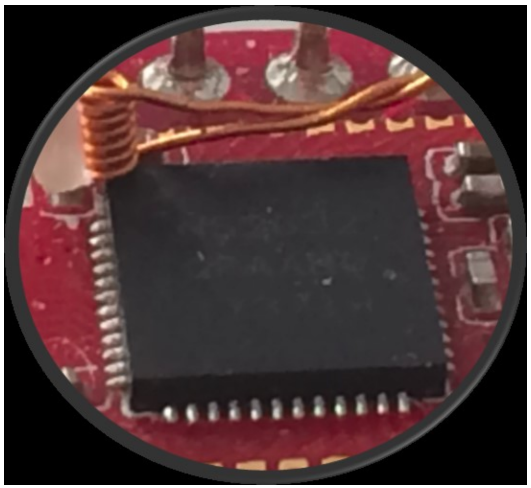
Conventional Side Channels



In Practice

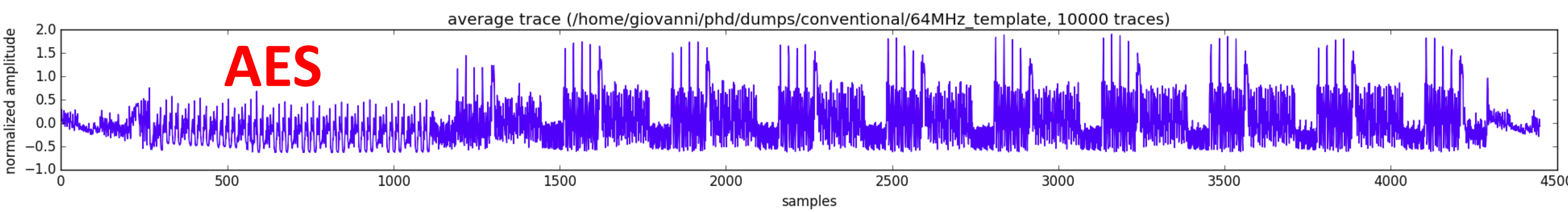


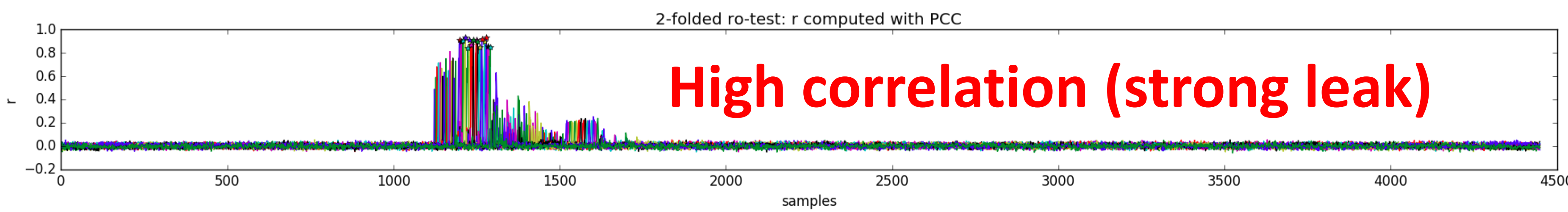
Collection

E.g. loop probe
+ oscilloscope

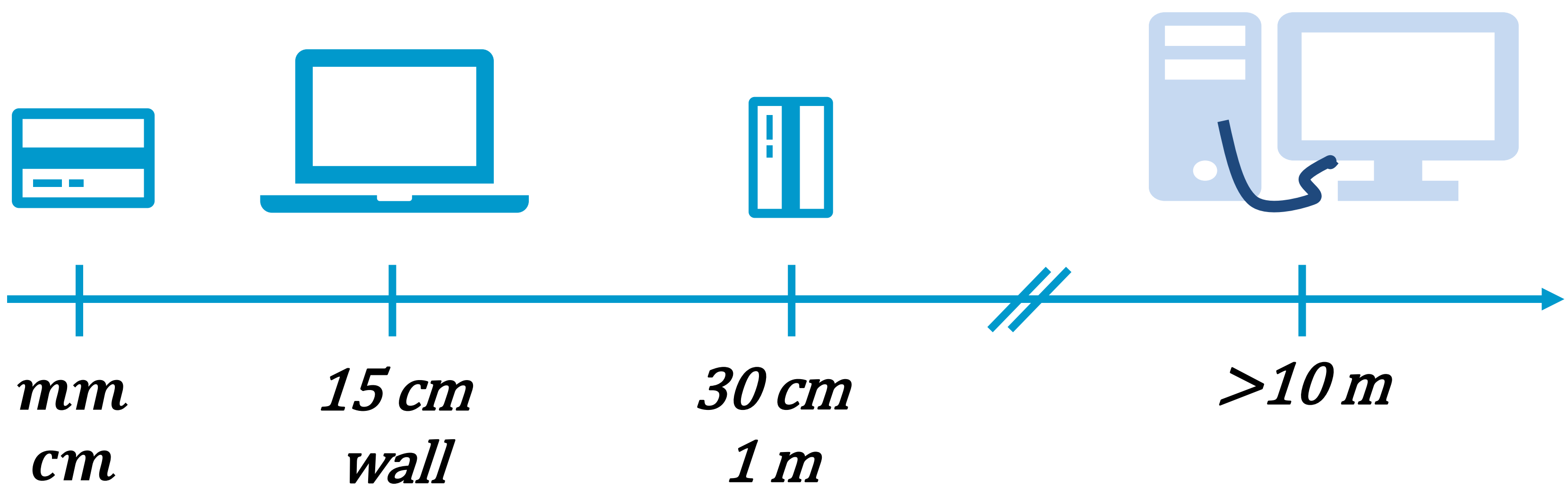
Many Analyses/Attacks

SPA, CPA, TPA, …
SEMA, CEMA, TEMA, …





Many Side Channels Involving EM



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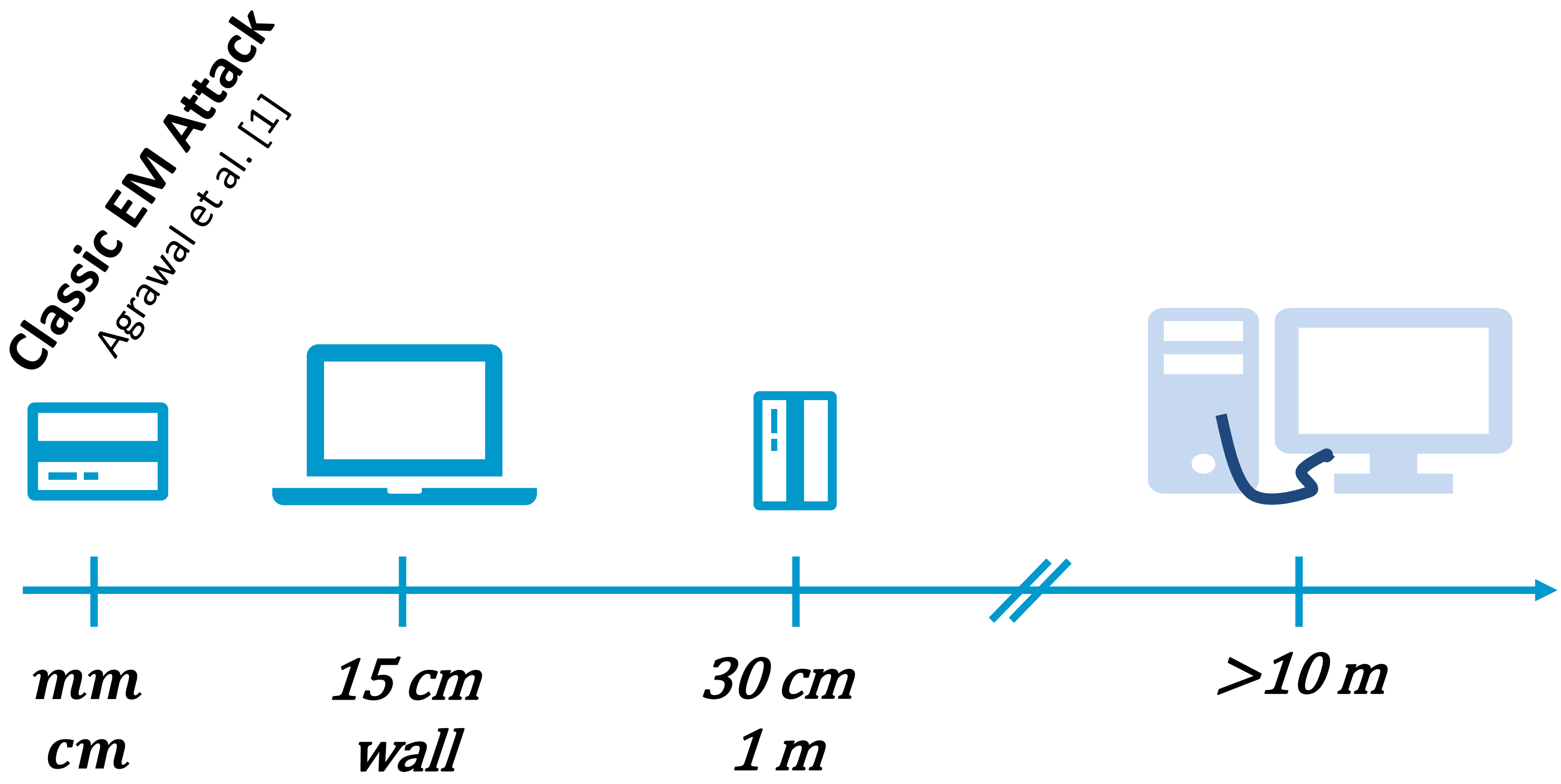

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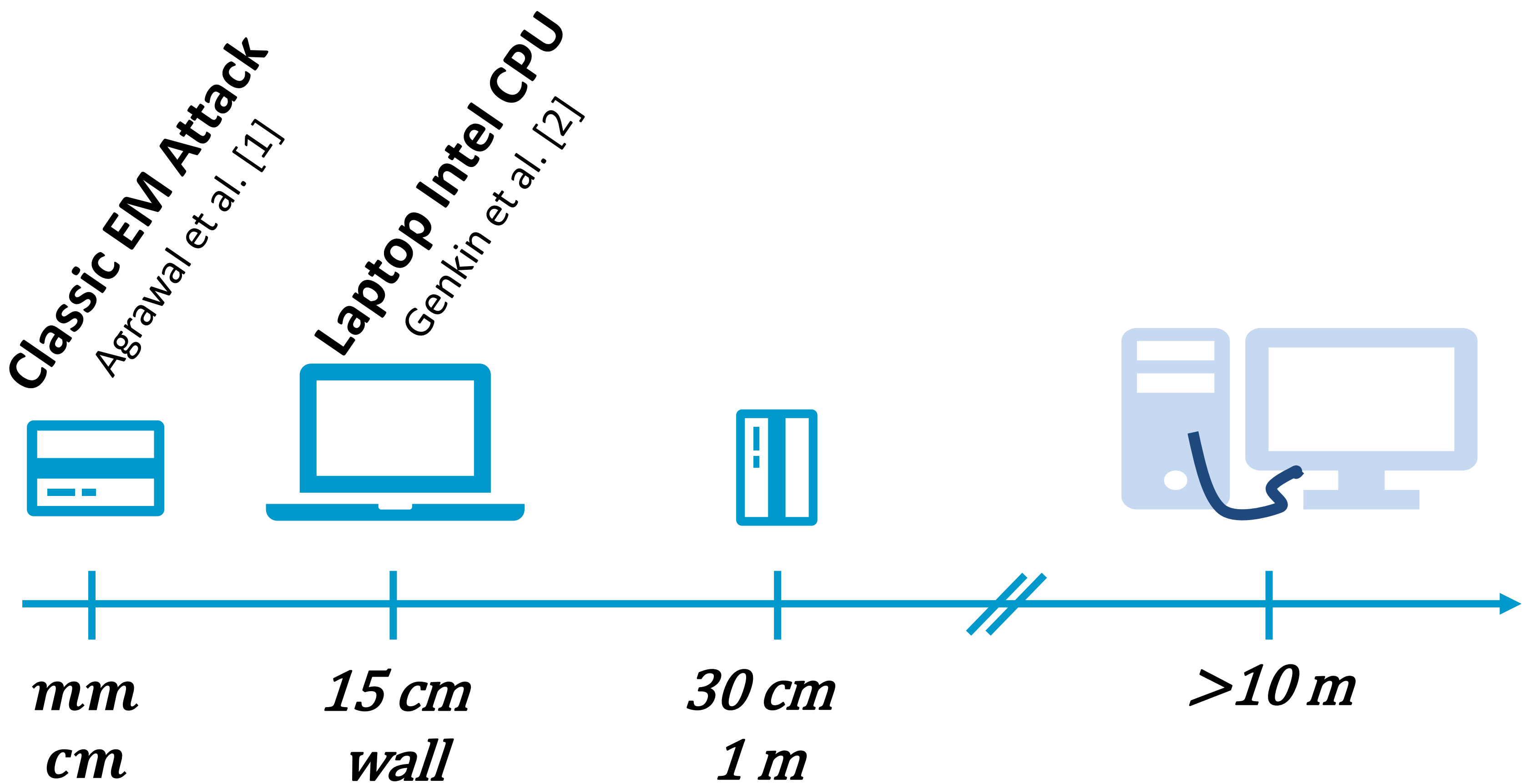

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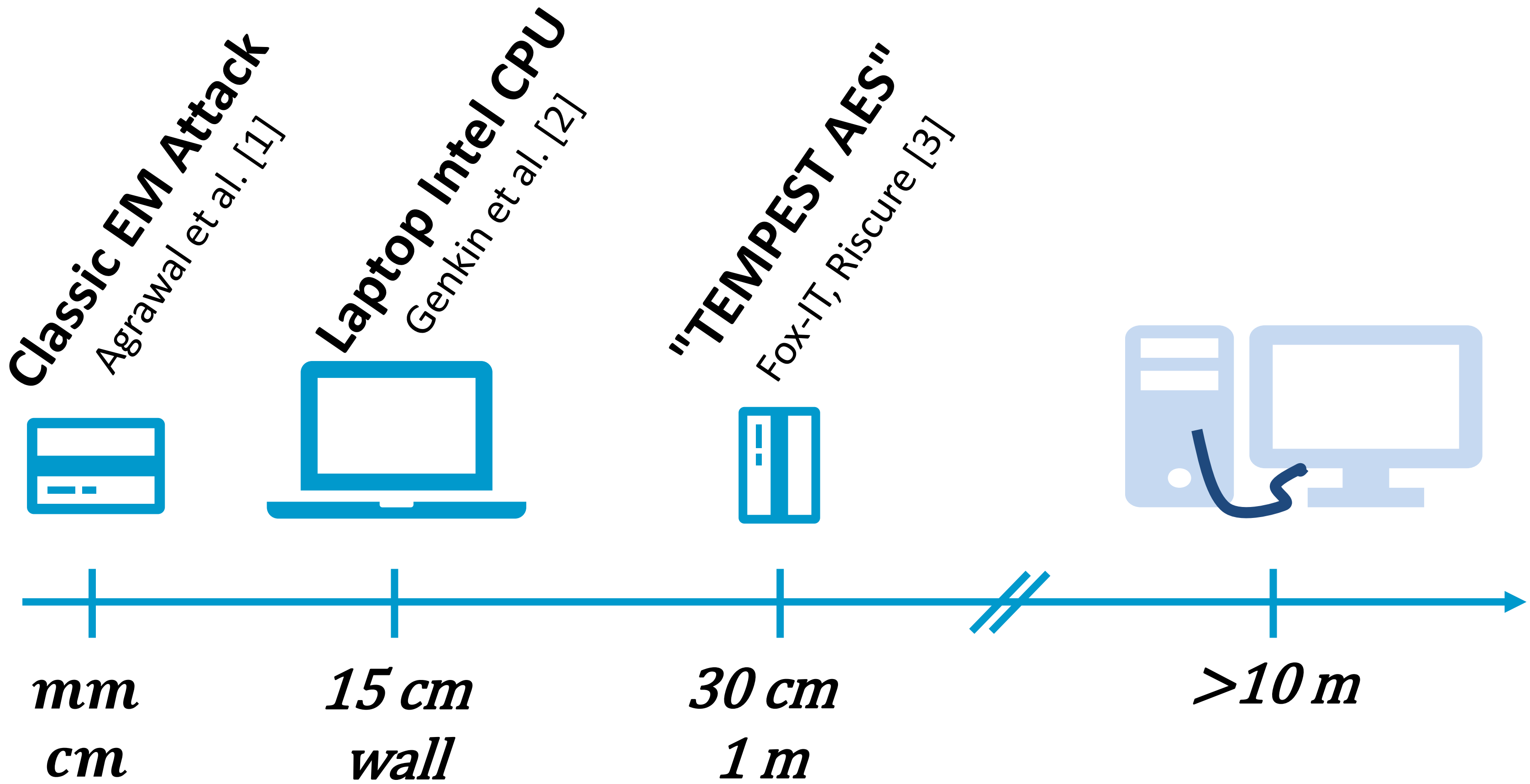

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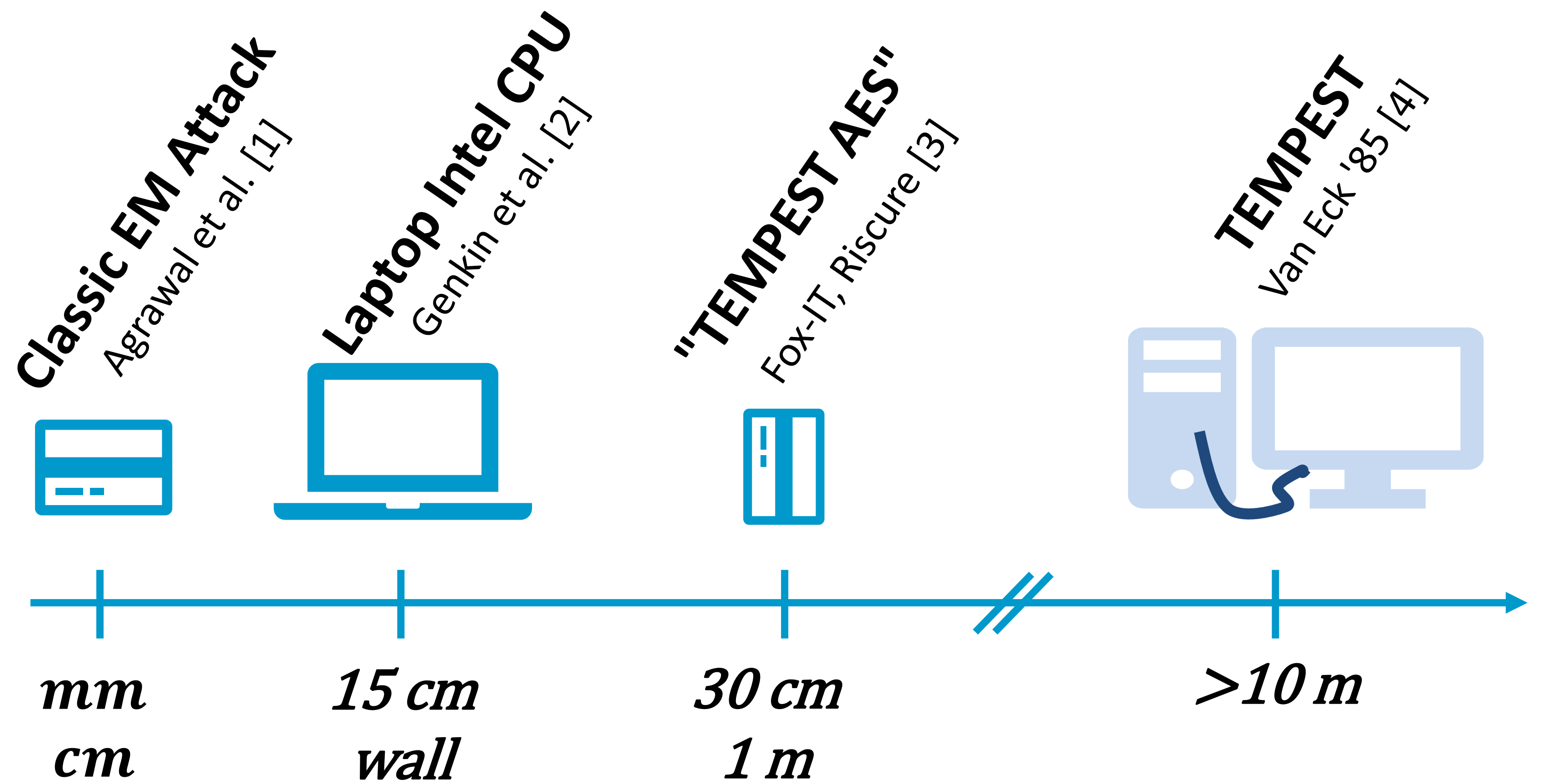

Many Side Channels Involving EM

Classic EM Attack
Agrawal et al. [1]

Laptop Intel CPU
Genkin et al. [2]

"TEMPEST AES"
Fox-IT, Riscure [3]

TEMPEST
...n Eck '85 [4]

mm
cm

15 cm
wall

30 cm
1 m

Many Side Channels In

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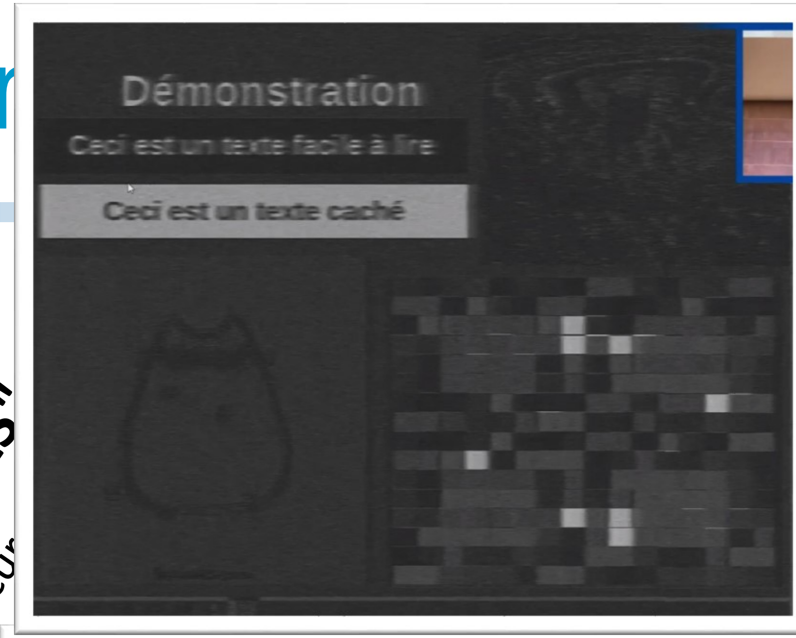

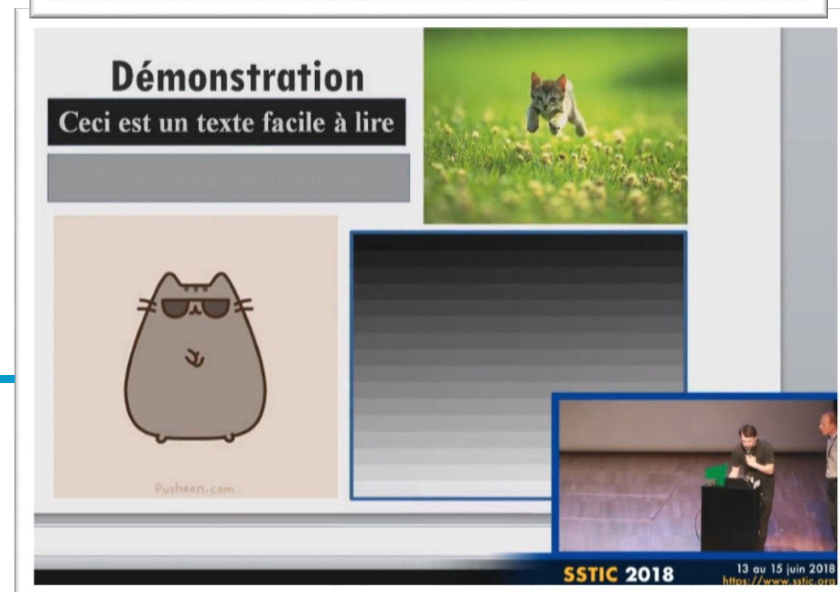

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Smart watch,
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Crypto protects the communication channel

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Connected devices:
Smart watch,
camera, ...

Crypto protects the
communication
channel

Only remote
attacks are
considered

Remote Side Channels

Remote Timing

Non constant time

Caches

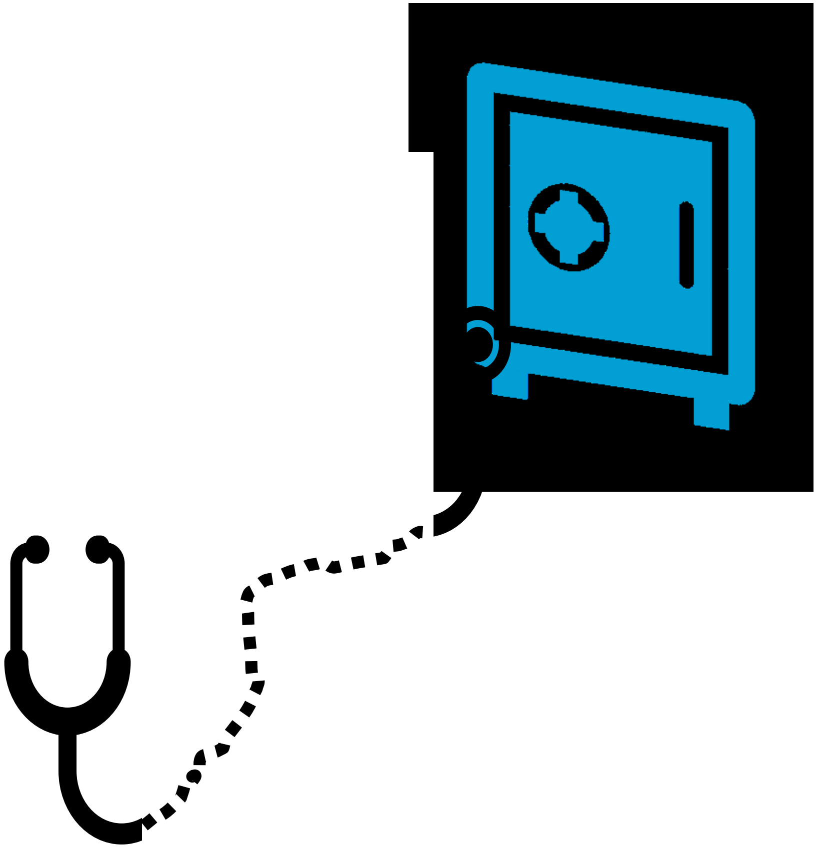
AES, TLS, …

WPA3 (Dragonblood)

EM?

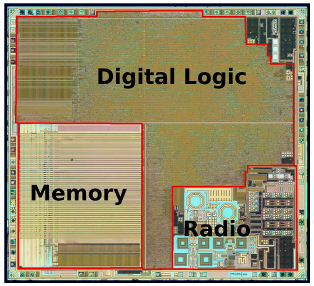
Physical access

Local



Problems When Adding Wireless Capabilities

Implementation: Mixed-signal Chips

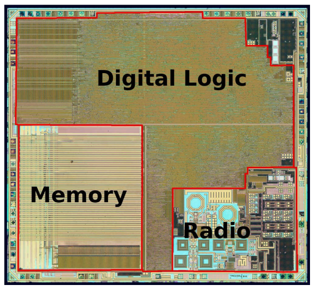


Idea:

CPU + Crypto + Radio

Same chip

Implementation: Mixed-signal Chips



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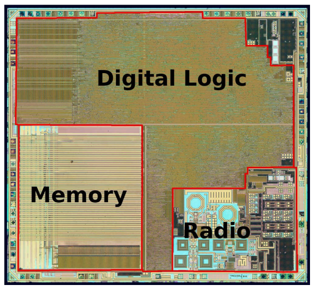
Benefits:
Low Power, Cheap, Small
Easy to integrate

Implementation: Mixed-signal Chips



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Examples:
BT, BLE, WiFi, GPS, etc

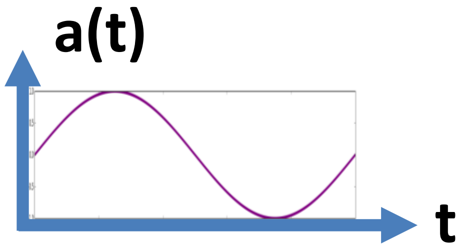
Issues

Reminder

Time vs. Frequency

Up-conversion

Issues



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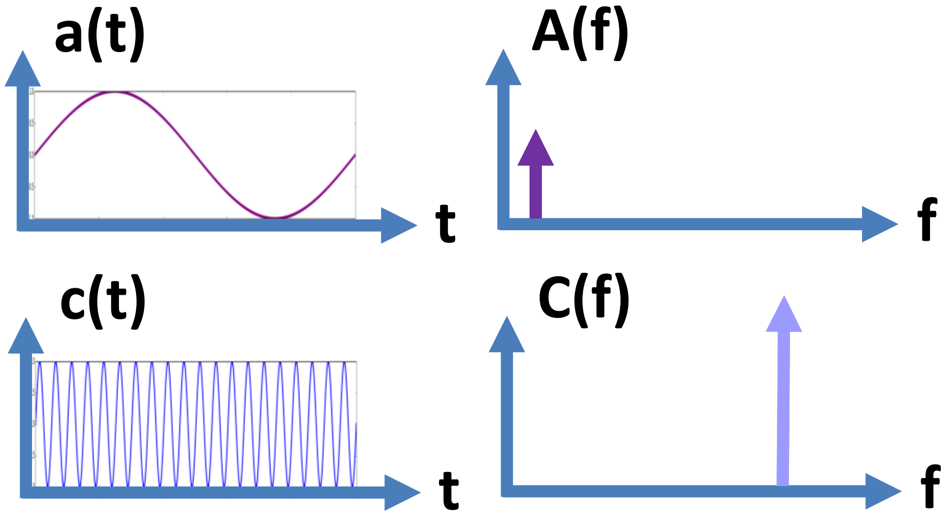

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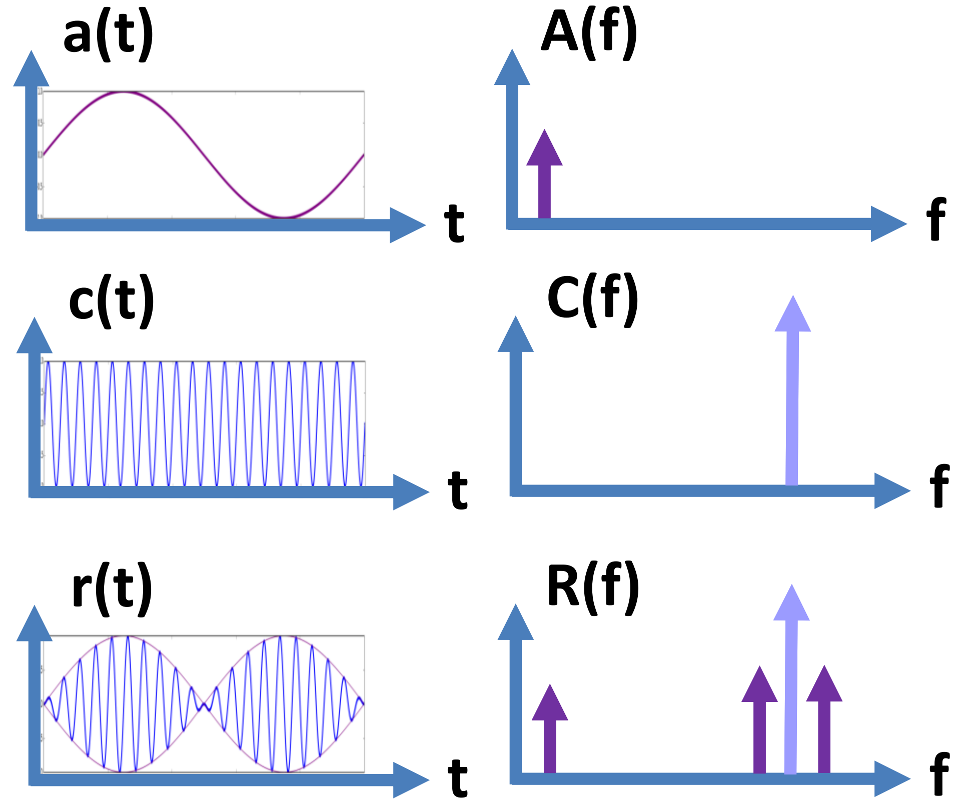

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Issues

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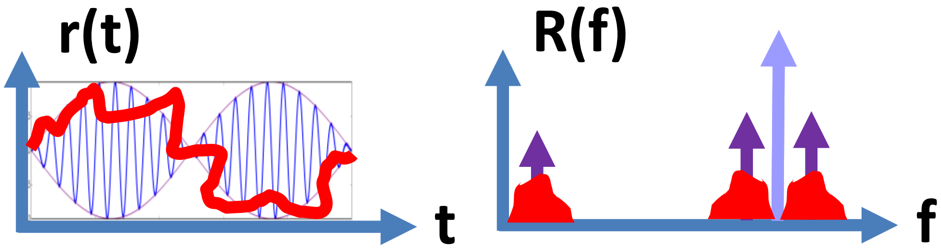
Issues

Analog/RF

Noise Sensitive



Issues

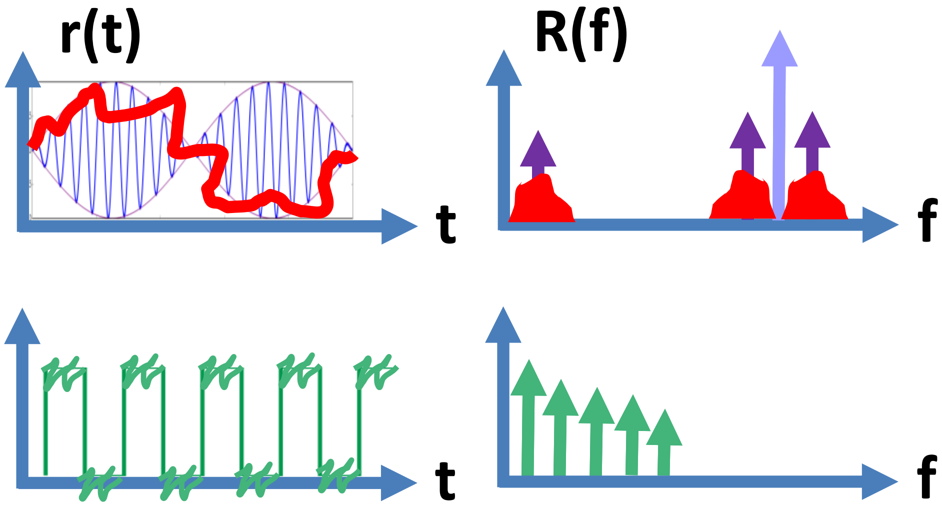
Analog/RF

Noise Sensitive

Digital

Noise resilient

Noise Source



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Noise resilient
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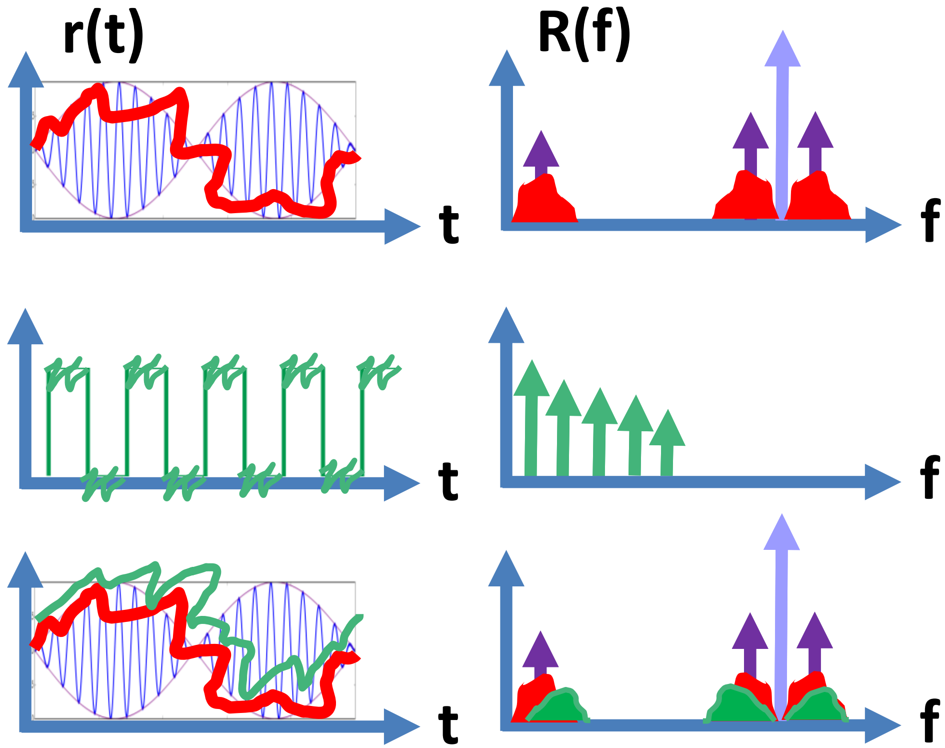
Same Chip
Noise Coupling



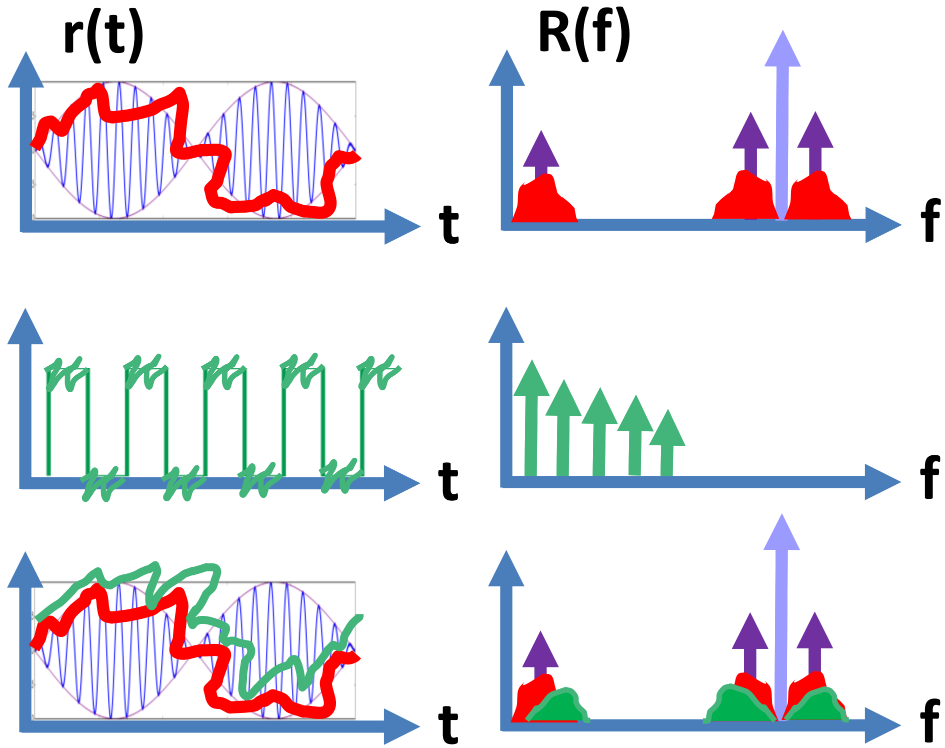
Issues

Analog/RF
Noise Sensitive

Digital
Noise resilient
Noise Source

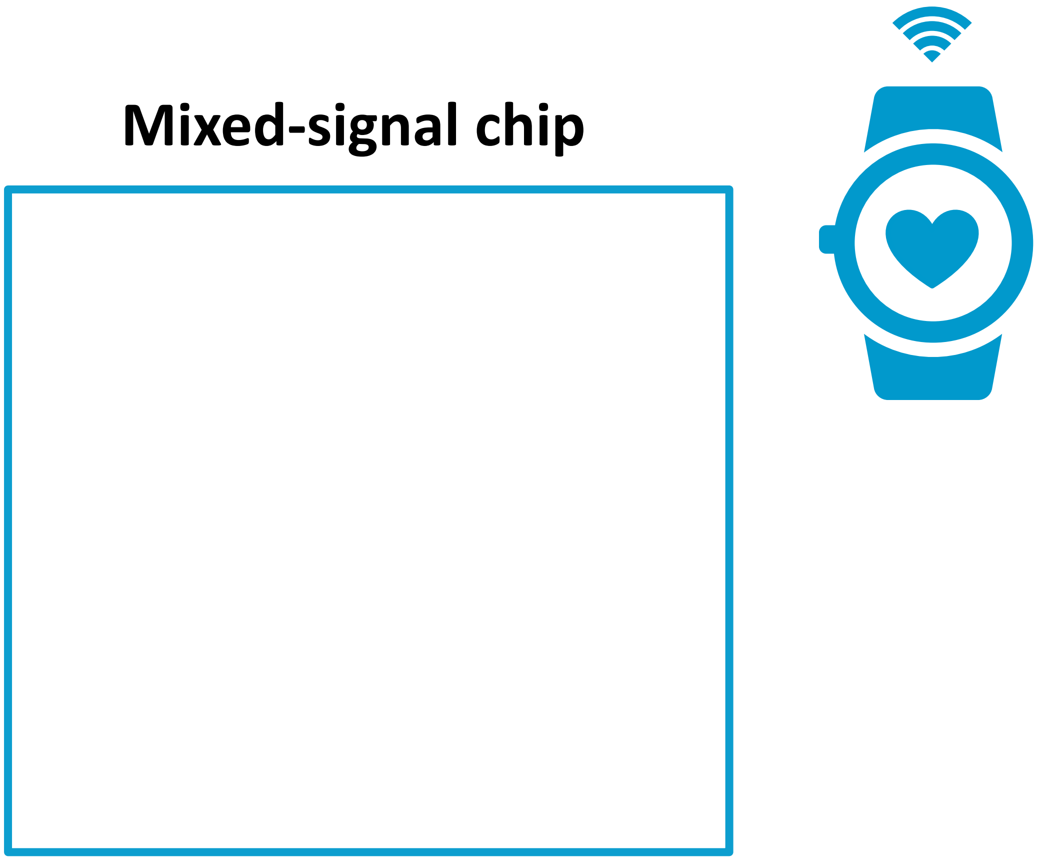
Same Chip
Noise Coupling

Careful Design
Radio Still Works



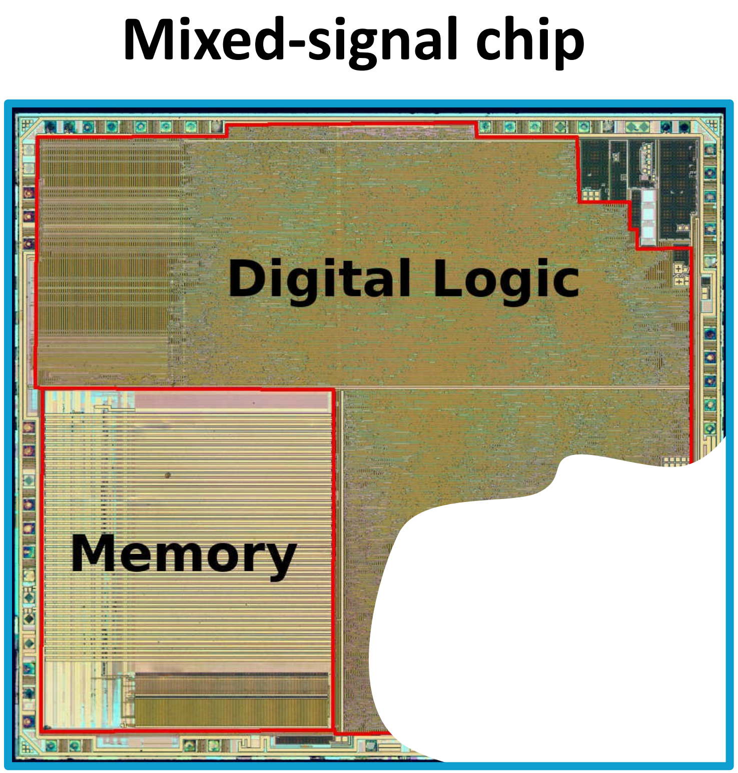
Problems, the global view

Mixed-signal chip



Problems, the global view

Strong noise source



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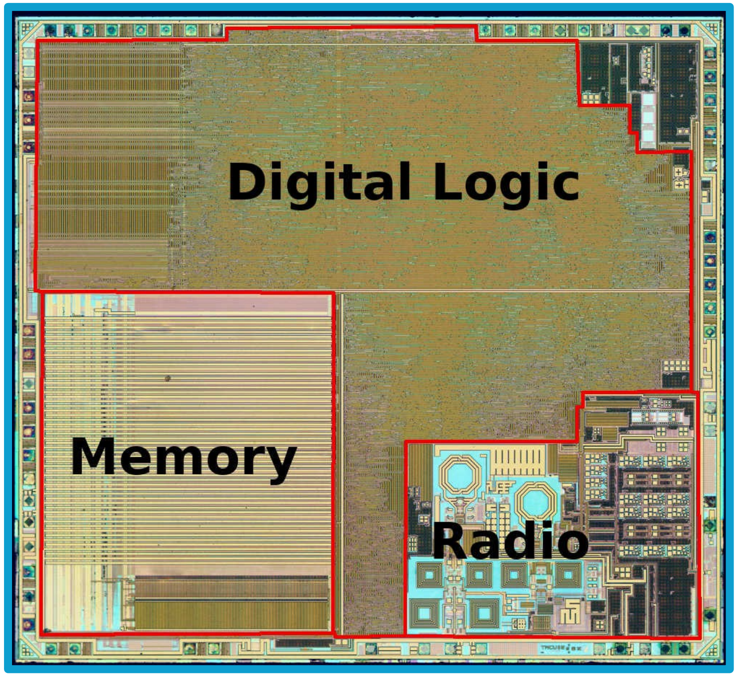
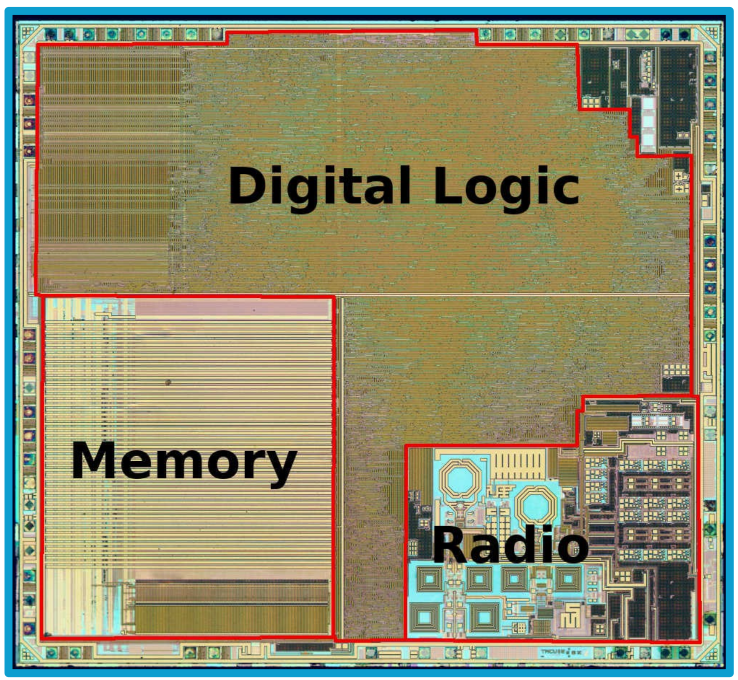


Noise sensitive transmitter

Problems, the global view

Mixed-signal chip

Strong noise source



Easy propagation

Noise sensitive transmitter

Screaming Channels
The Idea

Screaming Channels Idea

Mixed-signal chip

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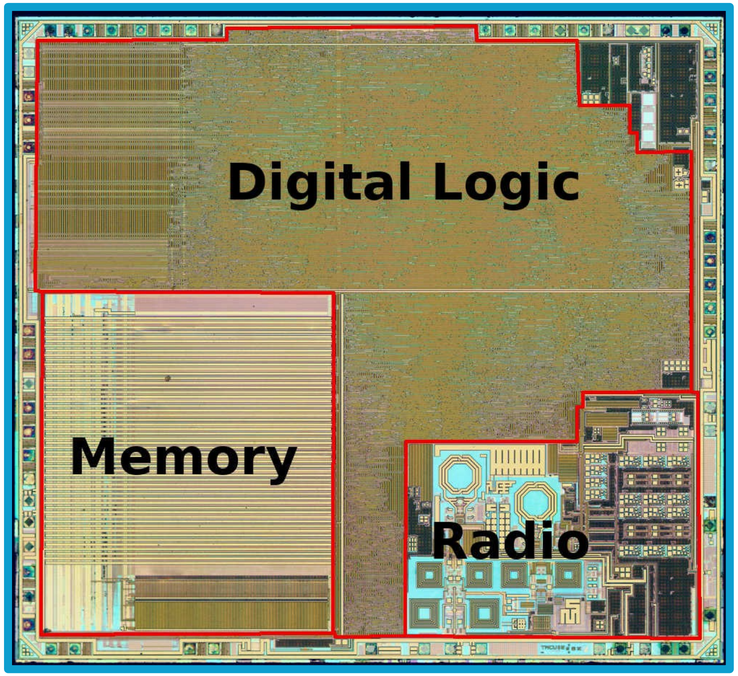

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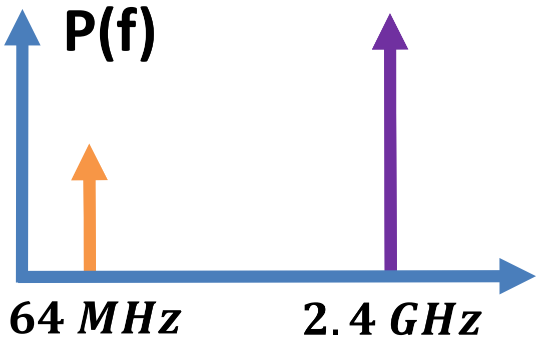


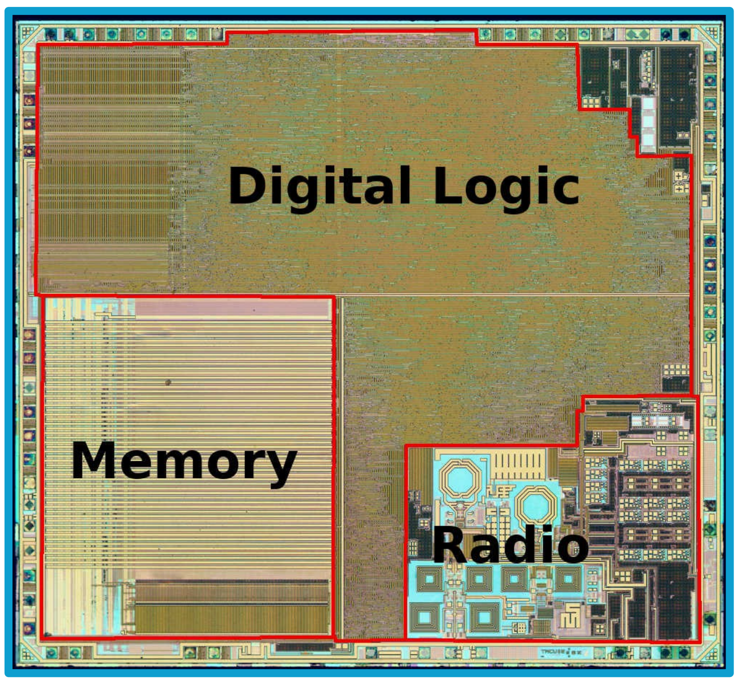
Noise sensitive transmitter

Screaming Channels Idea

Conventional Side Channel Leak

Mixed-signal chip

Strong noise source



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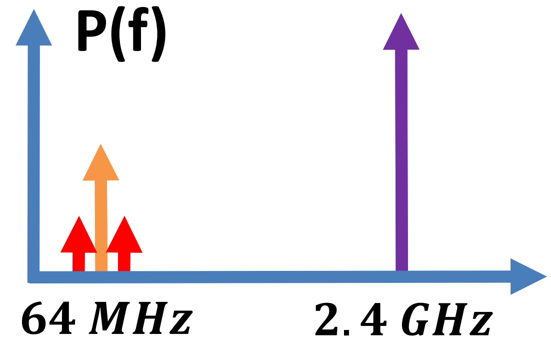

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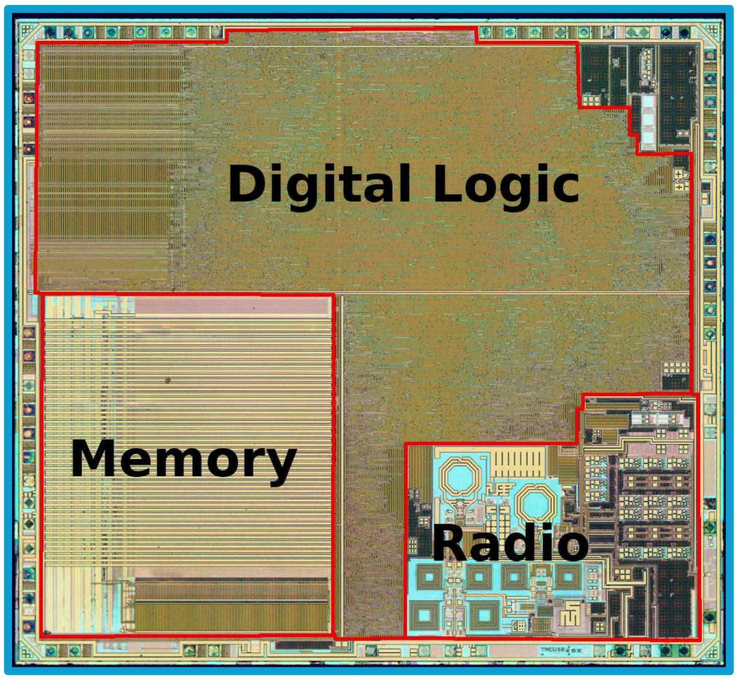
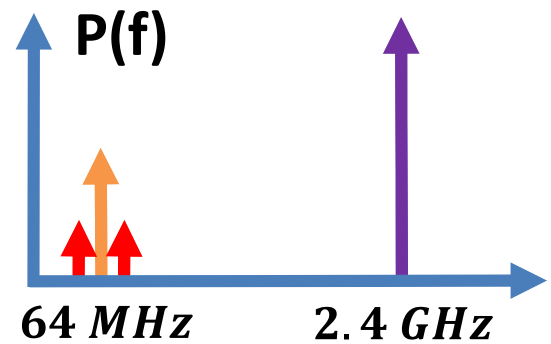


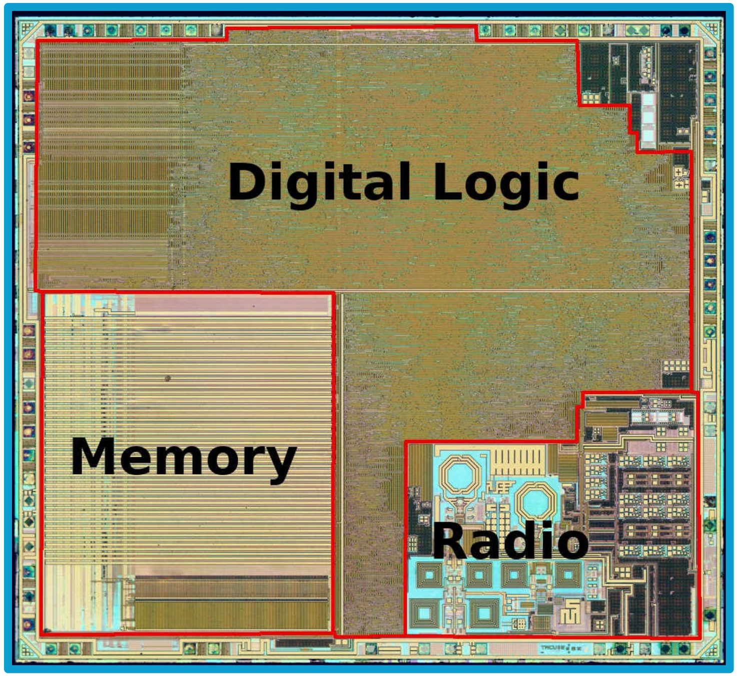


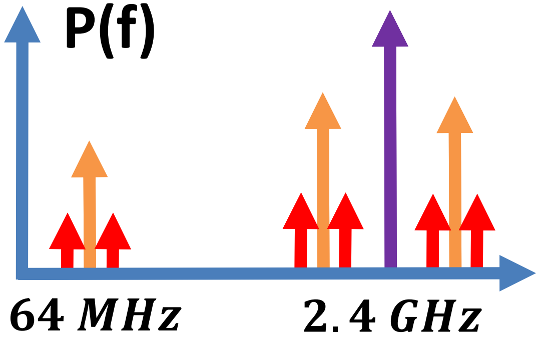
Noise sensitive transmitter

Easy propagation

Leak Propagation

Screaming Channels Idea





Noise sensitive transmitter

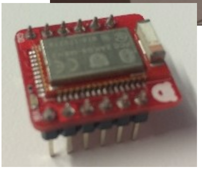
Leak Is Broadcast

Easy propagation

Leak Propagation

Screaming Channels in Action

Antenna + SDR RX



Cortex-M4
+ BT TX

Screaming Channels in Action

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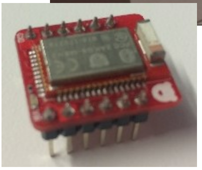
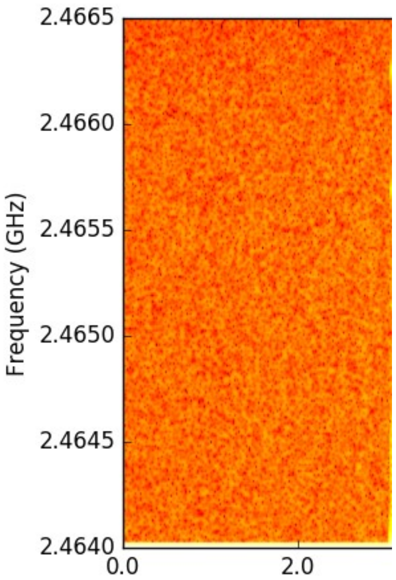


Cortex-M4 + BT TX

Radio Off



Noise

Screaming Channels in Action

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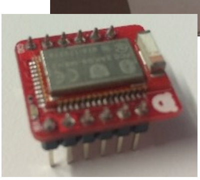
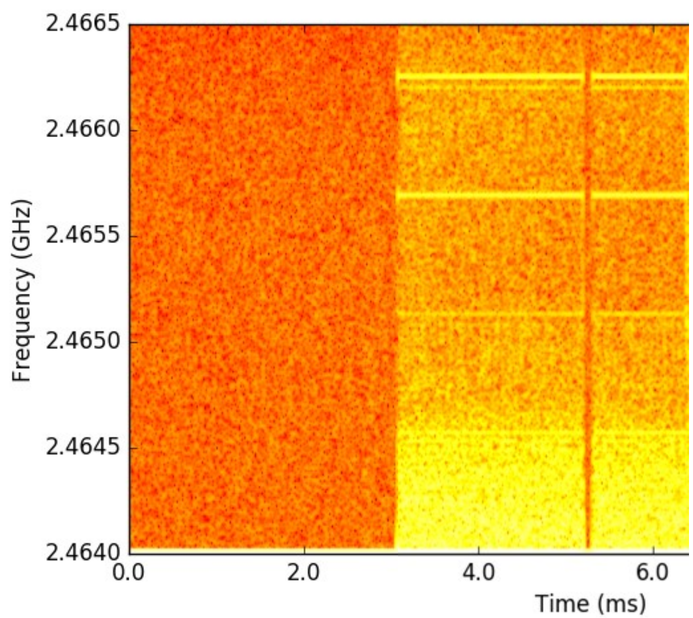


Cortex-M4 + BT TX

Radio Off **Radio TX**



Noise **Packet**

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Screaming Channels in Action

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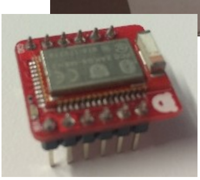

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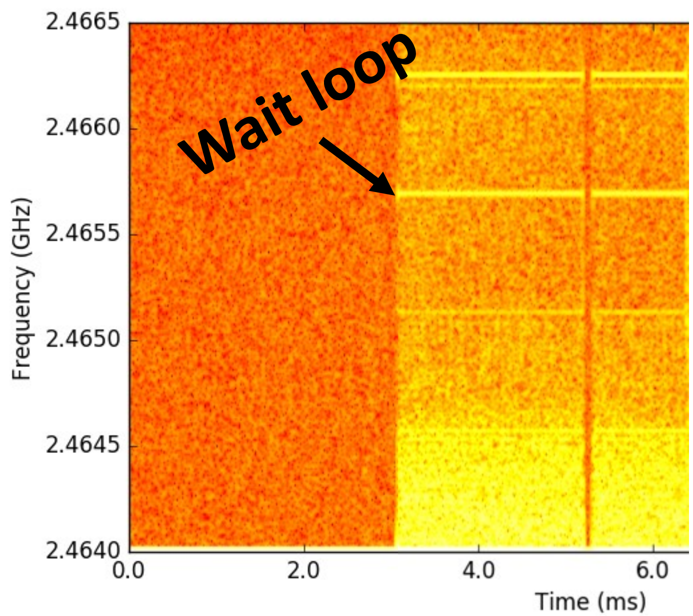

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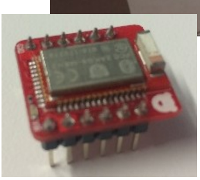

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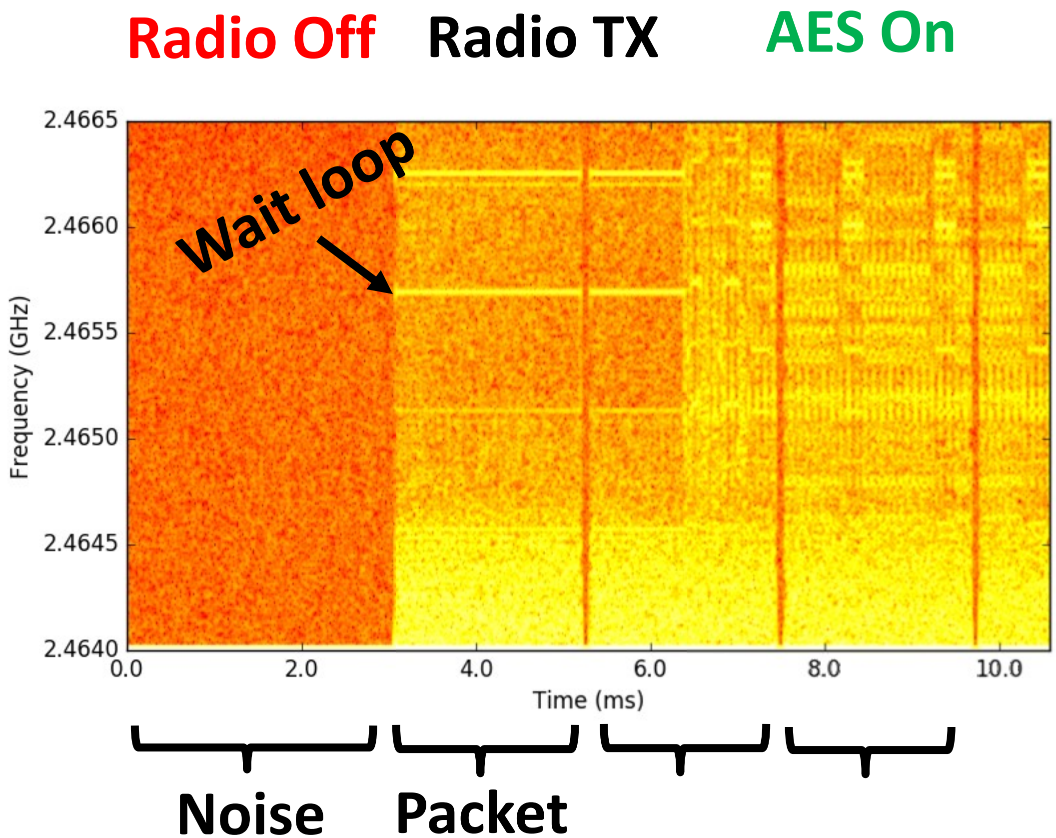

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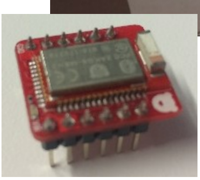
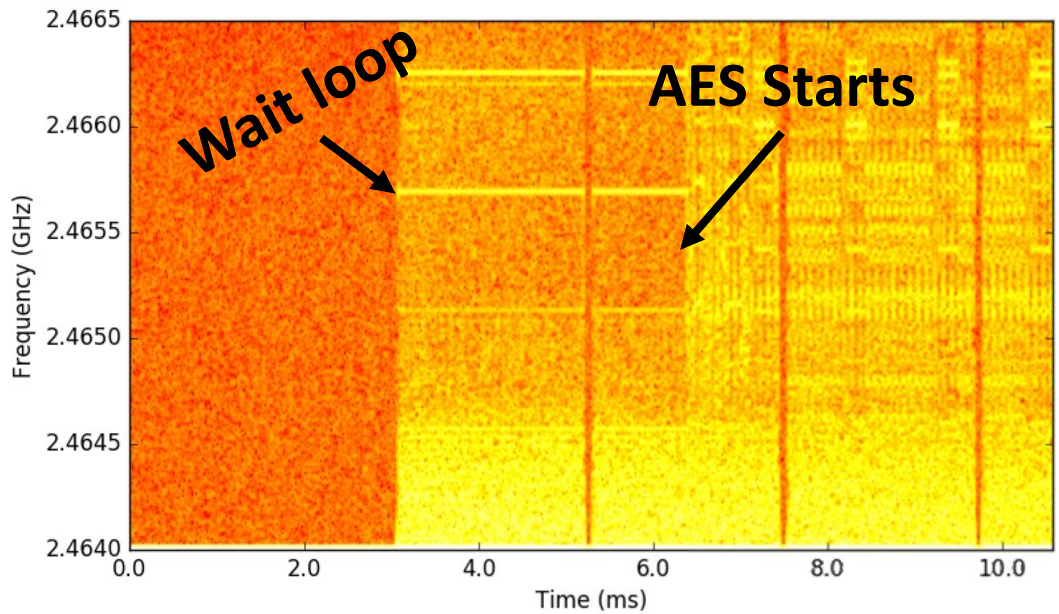


Cortex-M4 + BT TX

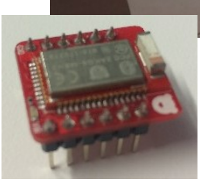
Radio Off **Radio TX** **AES On**



Noise **Packet**

Screaming Channels in Action

Antenna + SDR RX



Cortex-M4
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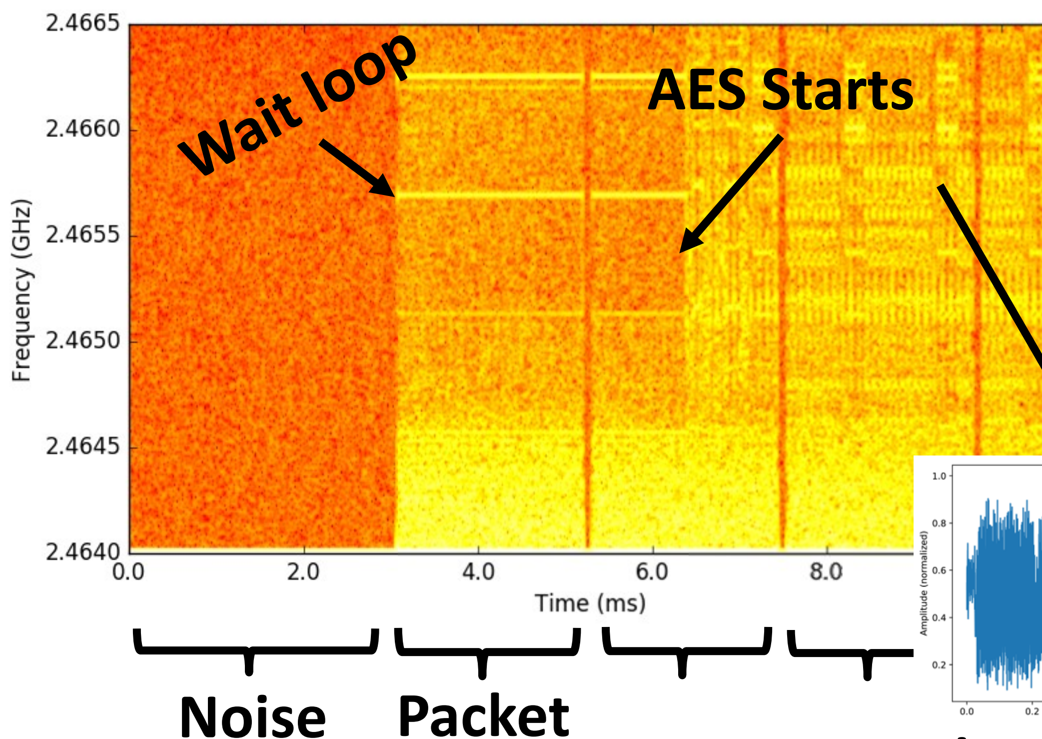
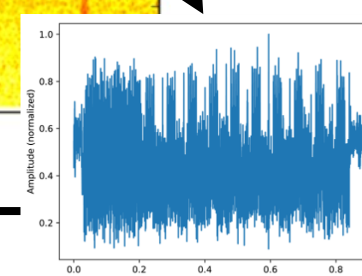
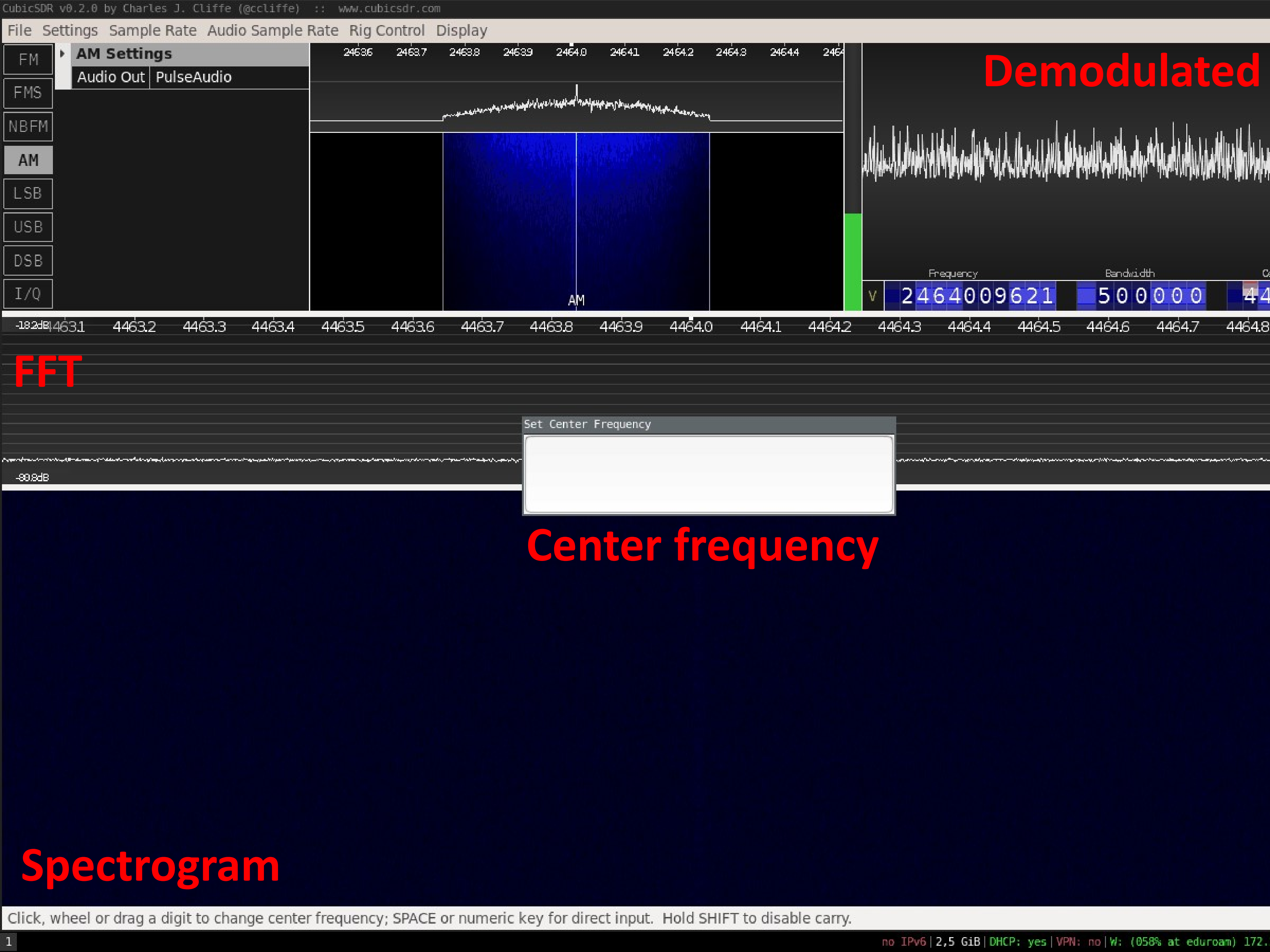
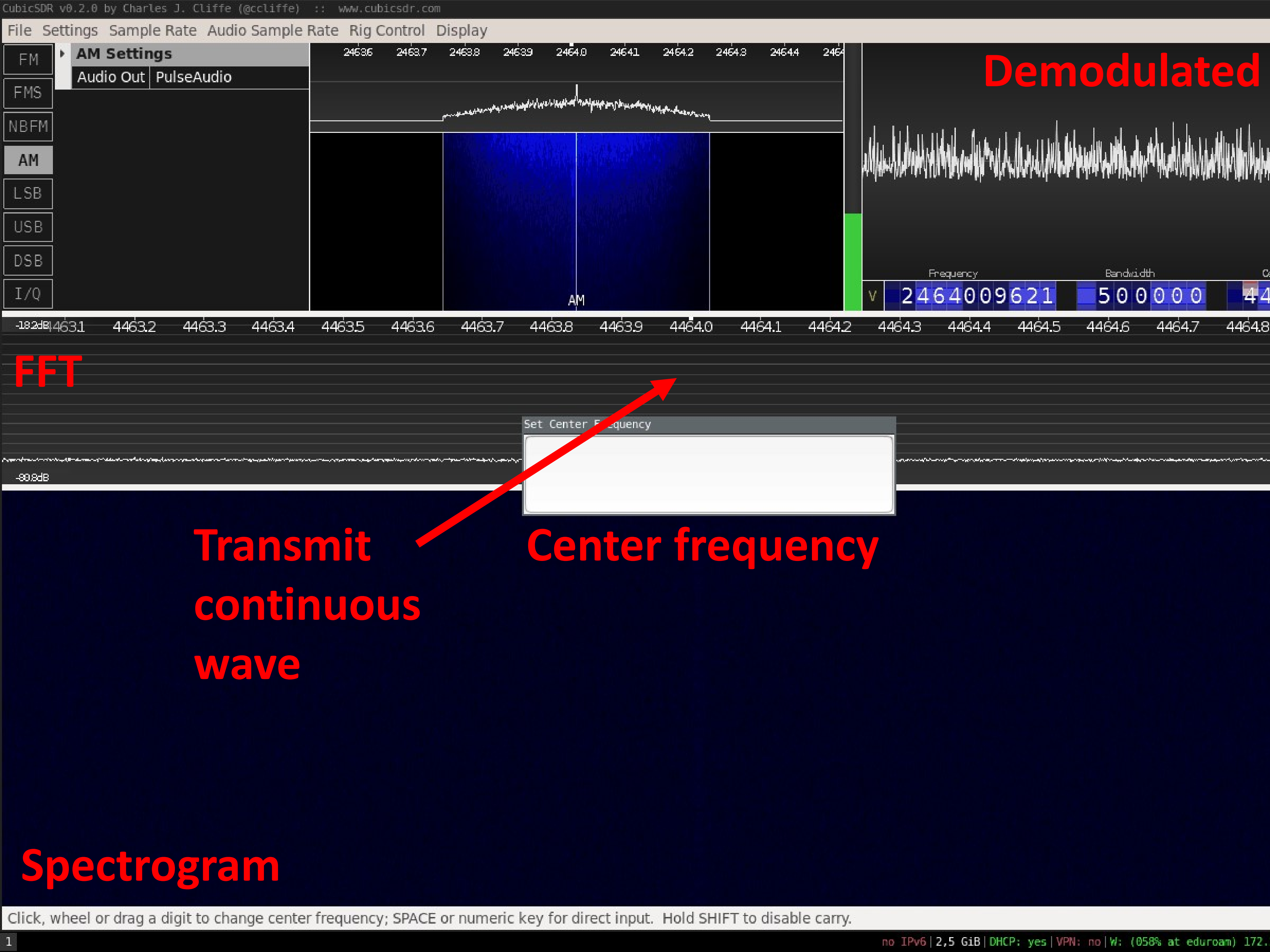




Time domain


CubicSDR v0.2.0 by Charles J. Cliffe (@ccliffe) :: www.cubicsdr.com
File Settings Sample Rate Audio Sample Rate Rig Control Display
FM
FMS
NBFM
AM
LSB
USB
DSB
I/Q
AM Settings
Audio Out PulseAudio
AM
Demodulated
Frequency
Bandwidth
2464009621
500000
FFT
Set Center Frequency
Center frequency
Spectrogram
Click, wheel or drag a digit to change center frequency; SPACE or numeric key for direct input. Hold SHIFT to disable carry.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File Settings Sample Rate Audio Sample Rate Rig Control Display
FM
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I/Q
AM Settings
Audio Out PulseAudio
AM
Demodulated
Frequency
Bandwidth
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500000
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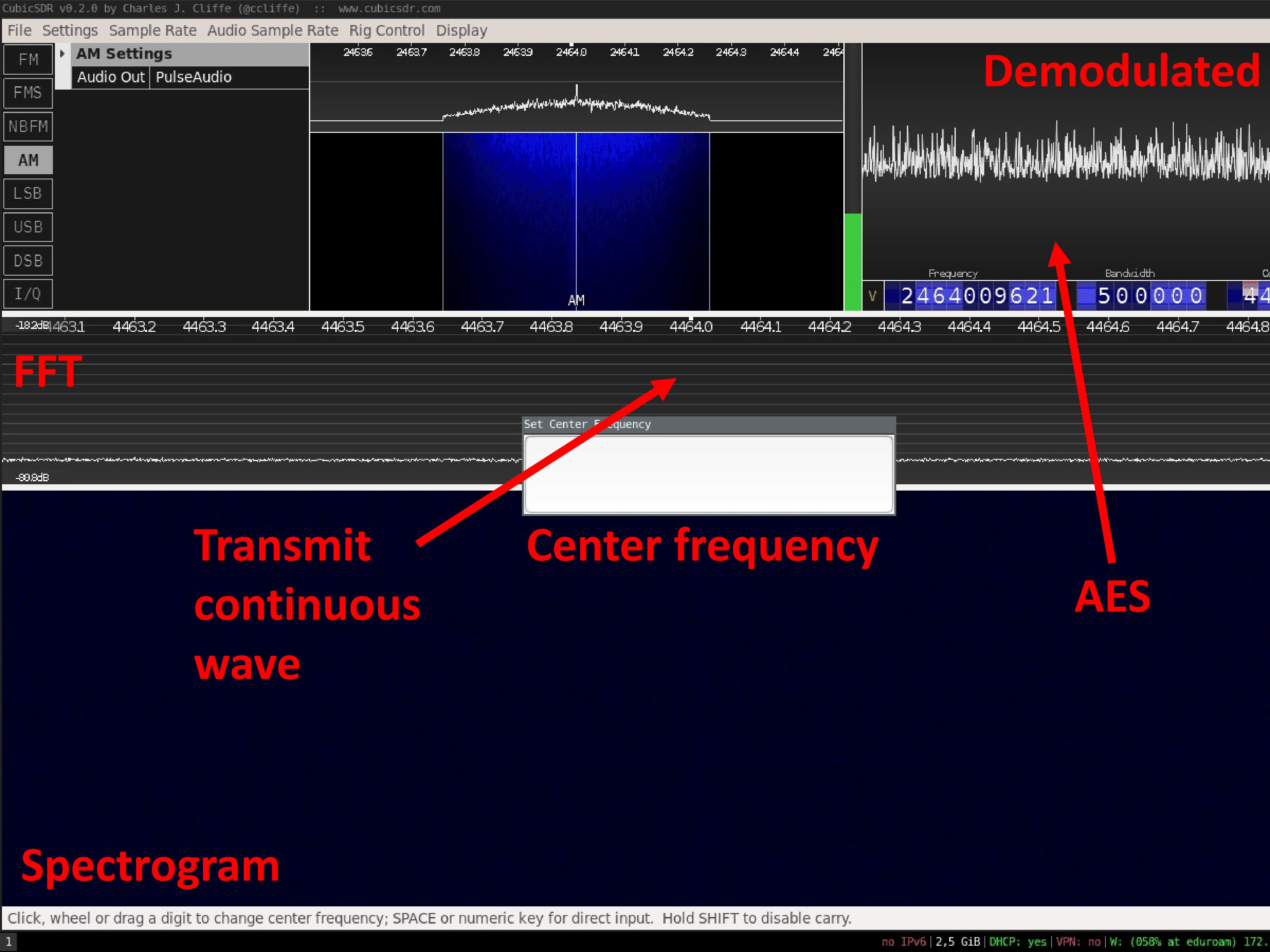
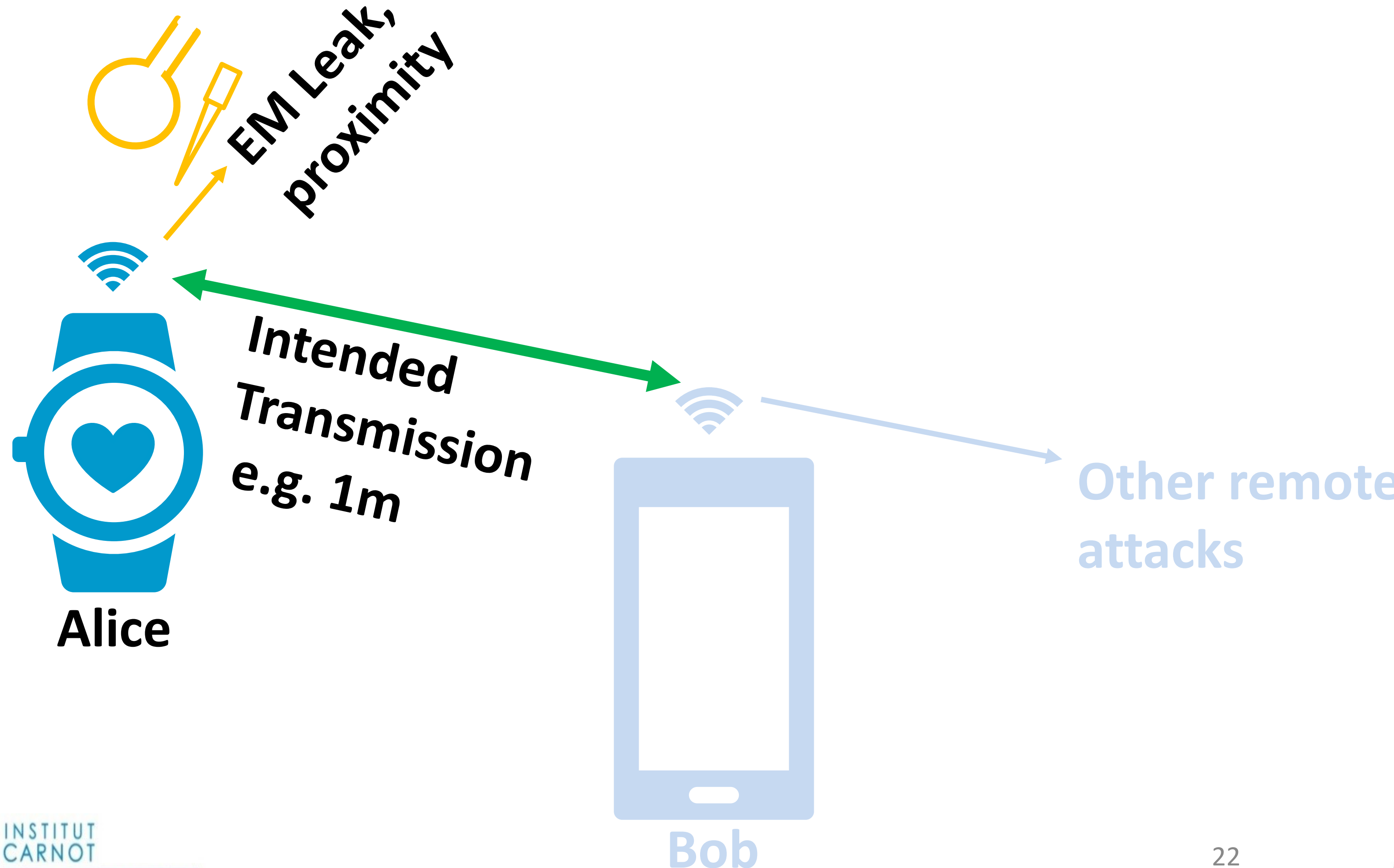
Spectrogram
Click, wheel or drag a digit to change center frequency; SPACE or numeric key for direct input. Hold SHIFT to disable carry.

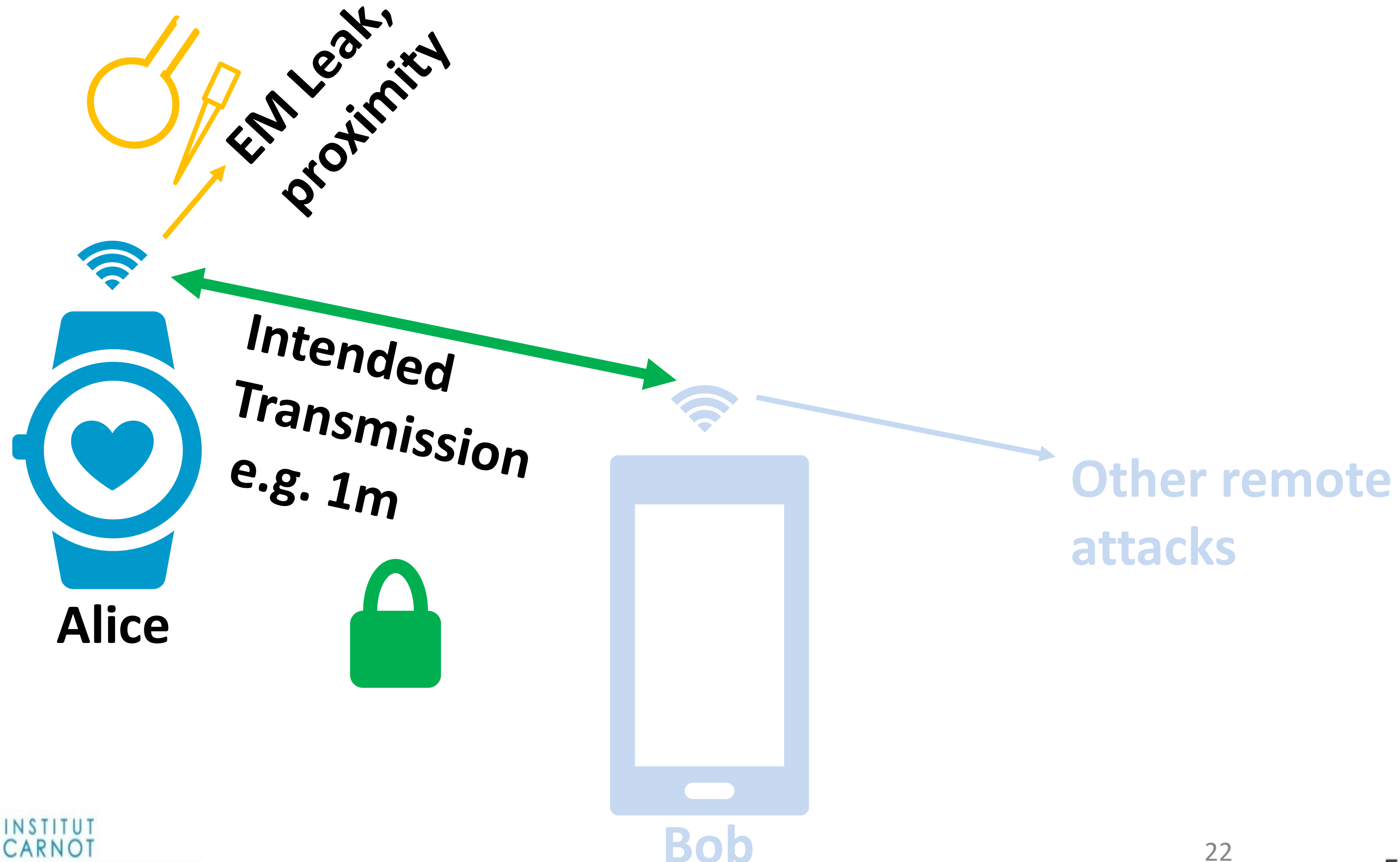


CubicSDR v0.2.0 by Charles J. Cliffe (@ccliffe) :: www.cubicsdr.com
File Settings Sample Rate Audio Sample Rate Rig Control Display
FM
FMS
NBFM
AM
LSB
USB
DSB
I/Q
AM Settings
Audio Out PulseAudio
Demodulated
Frequency
Bandwidth
2464009621
500000
AM
FFT
Set Center Frequency
Transmit continuous wave
Center frequency
AES
Spectrogram
Click, wheel or drag a digit to change center frequency; SPACE or numeric key for direct input. Hold SHIFT to disable carry.

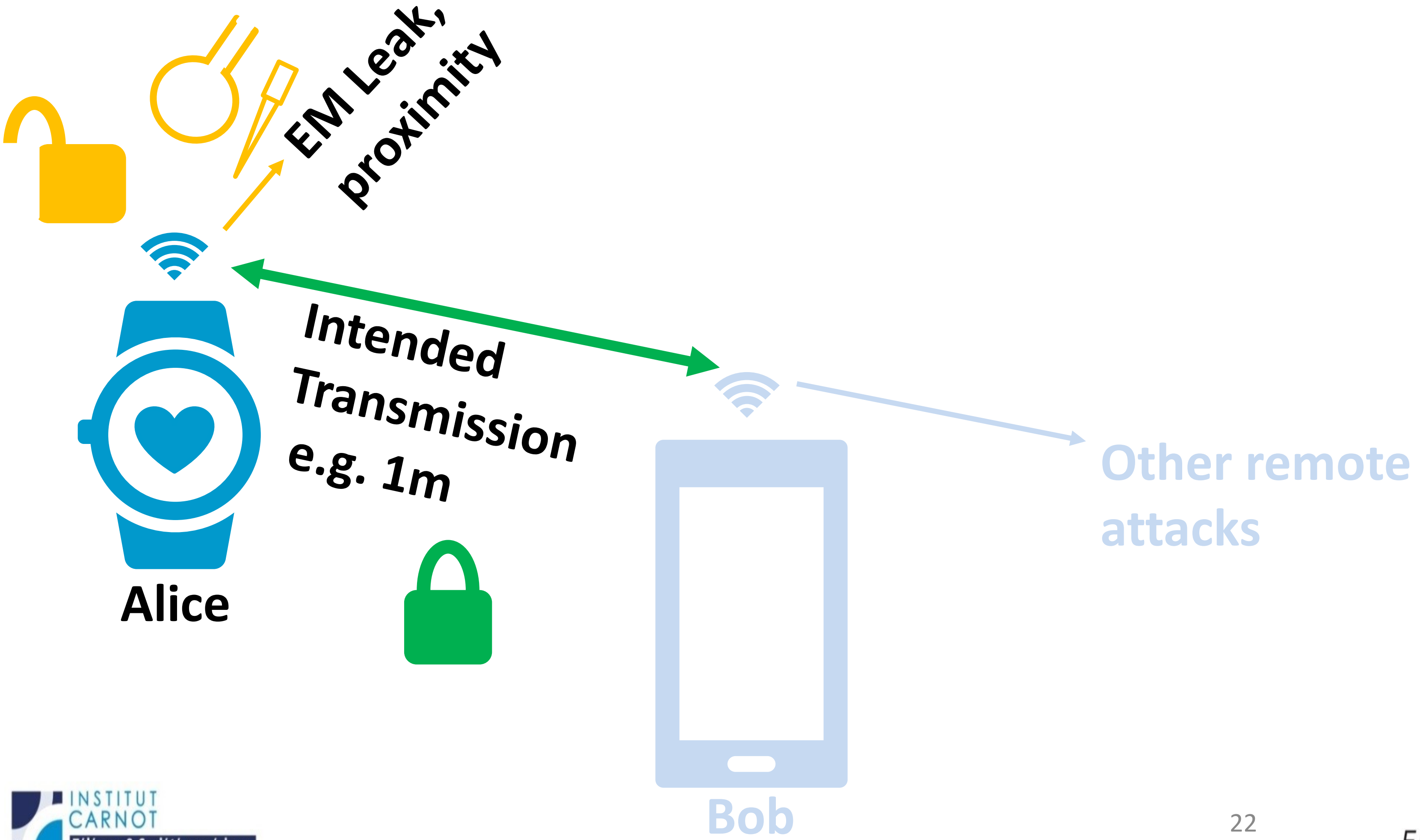
Screaming Channels: Leak Broadcast



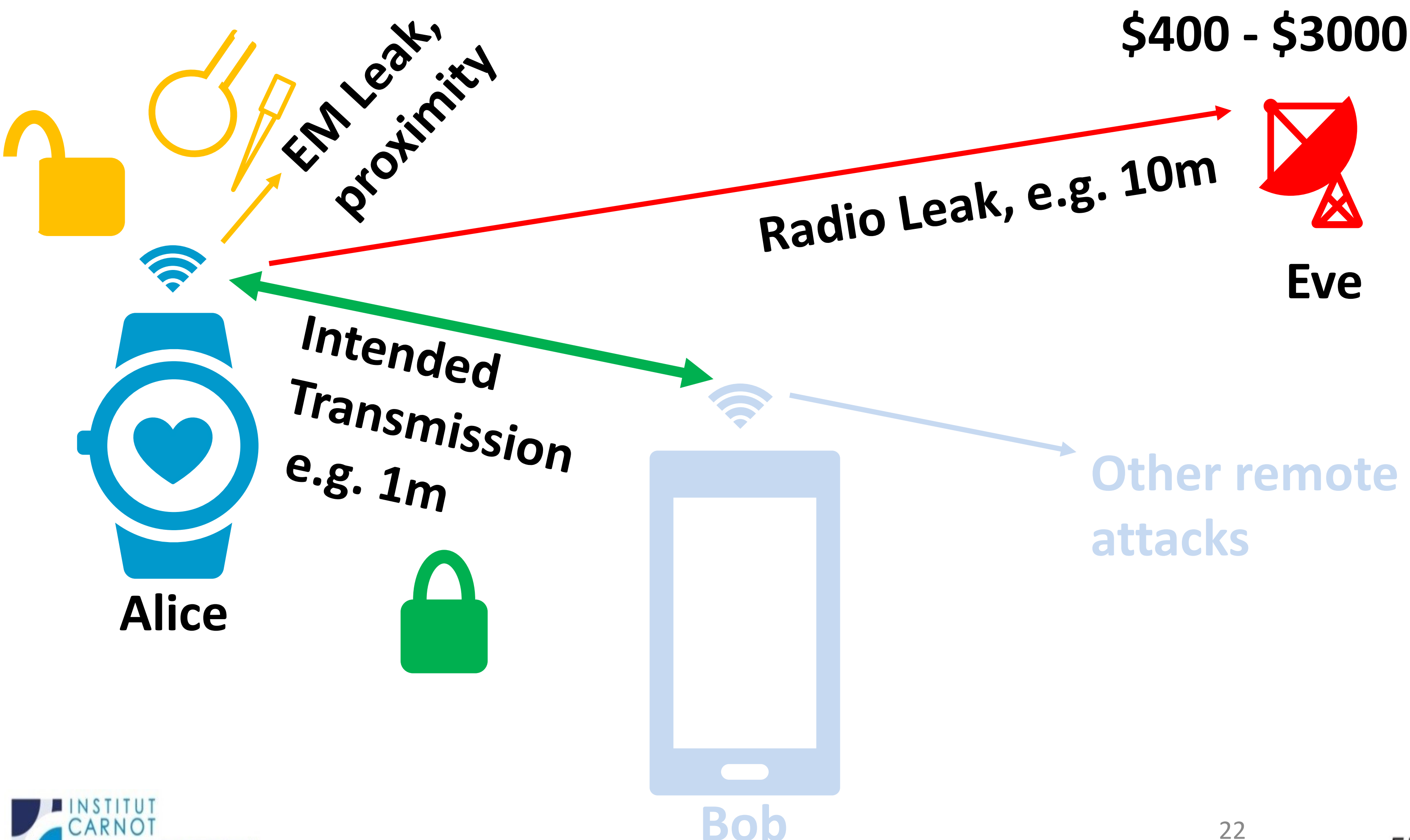
Screaming Channels: Leak Broadcast



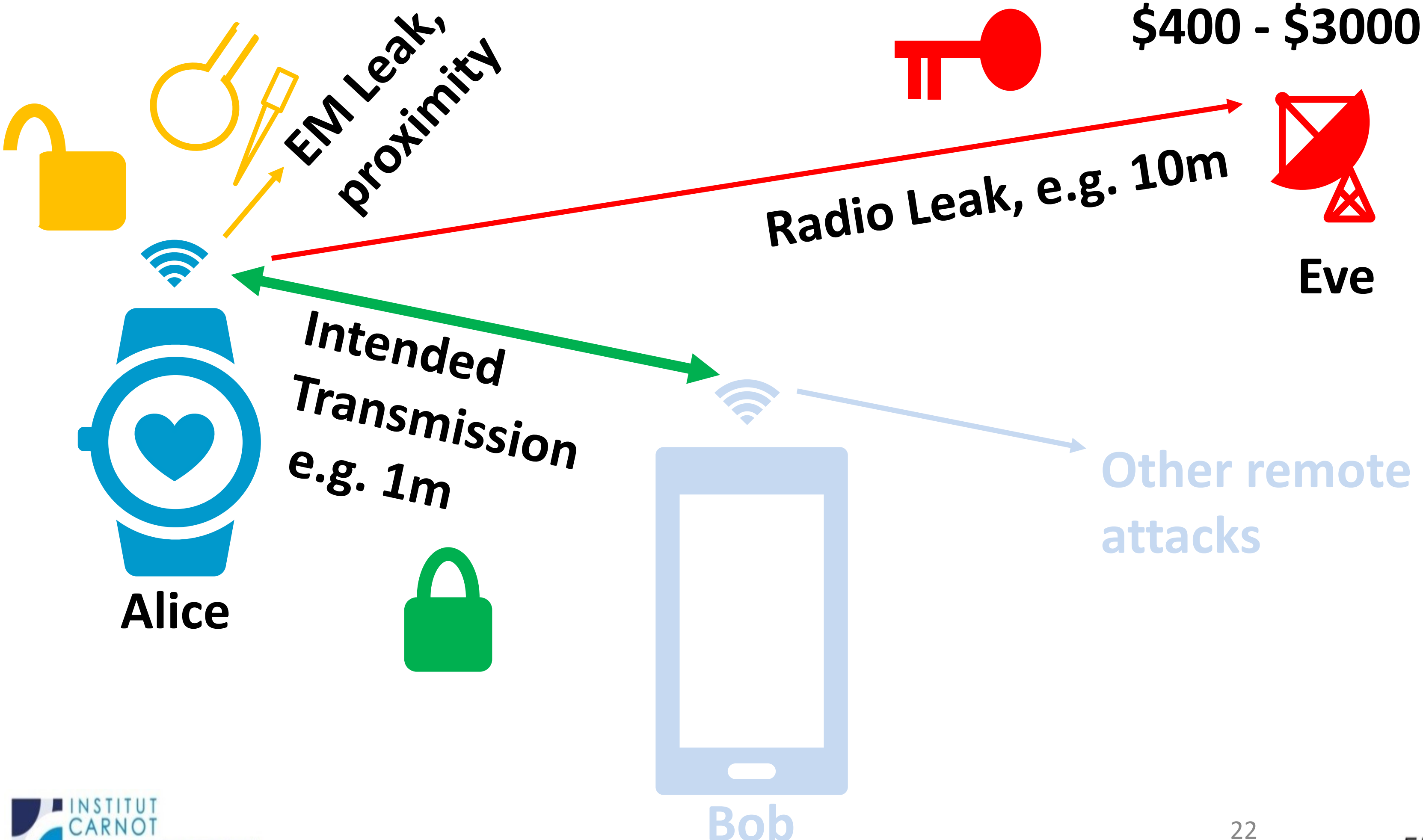
Screaming Channels: Leak Broadcast



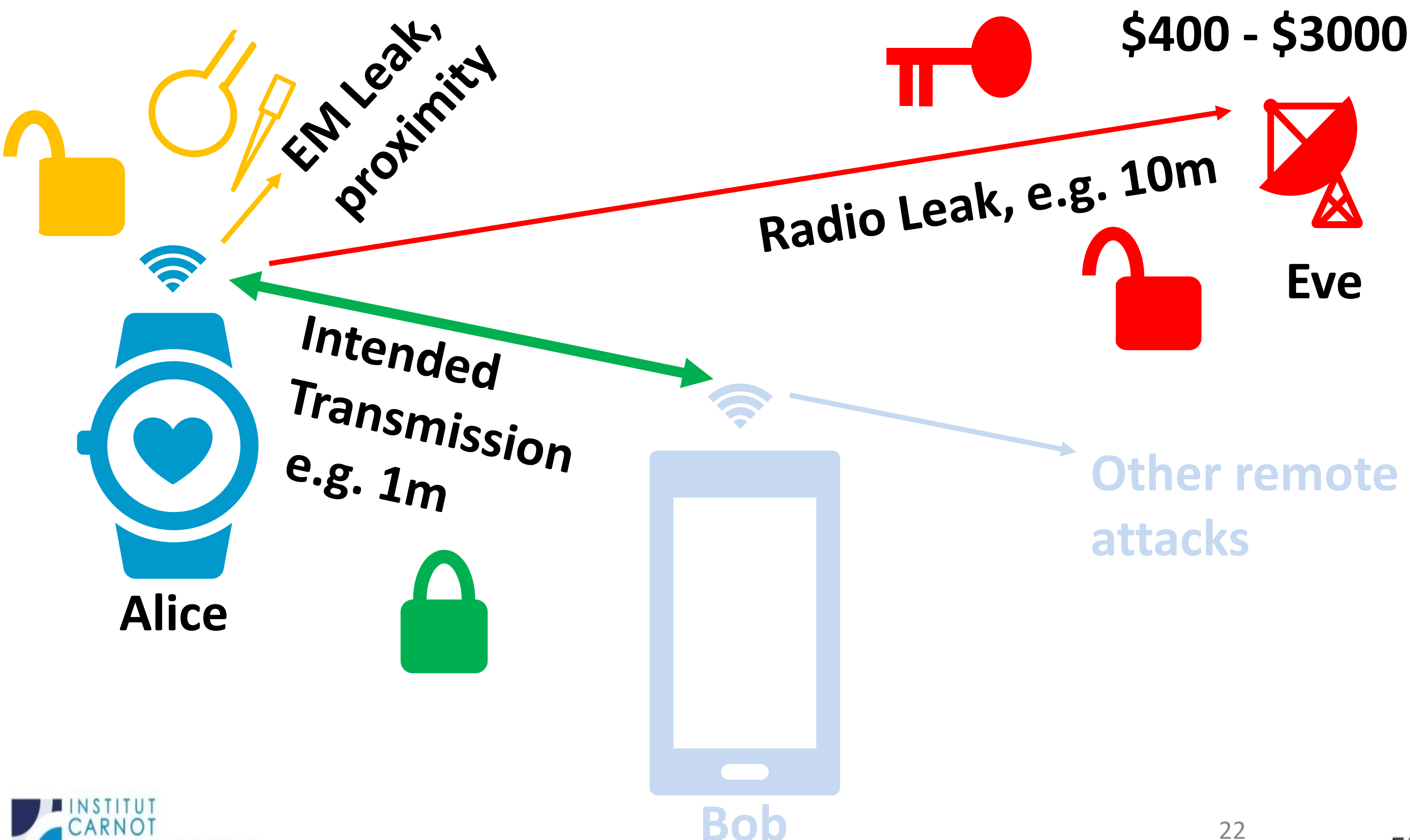
Screaming Channels: Leak Broadcast



Screaming Channels: Leak Broadcast

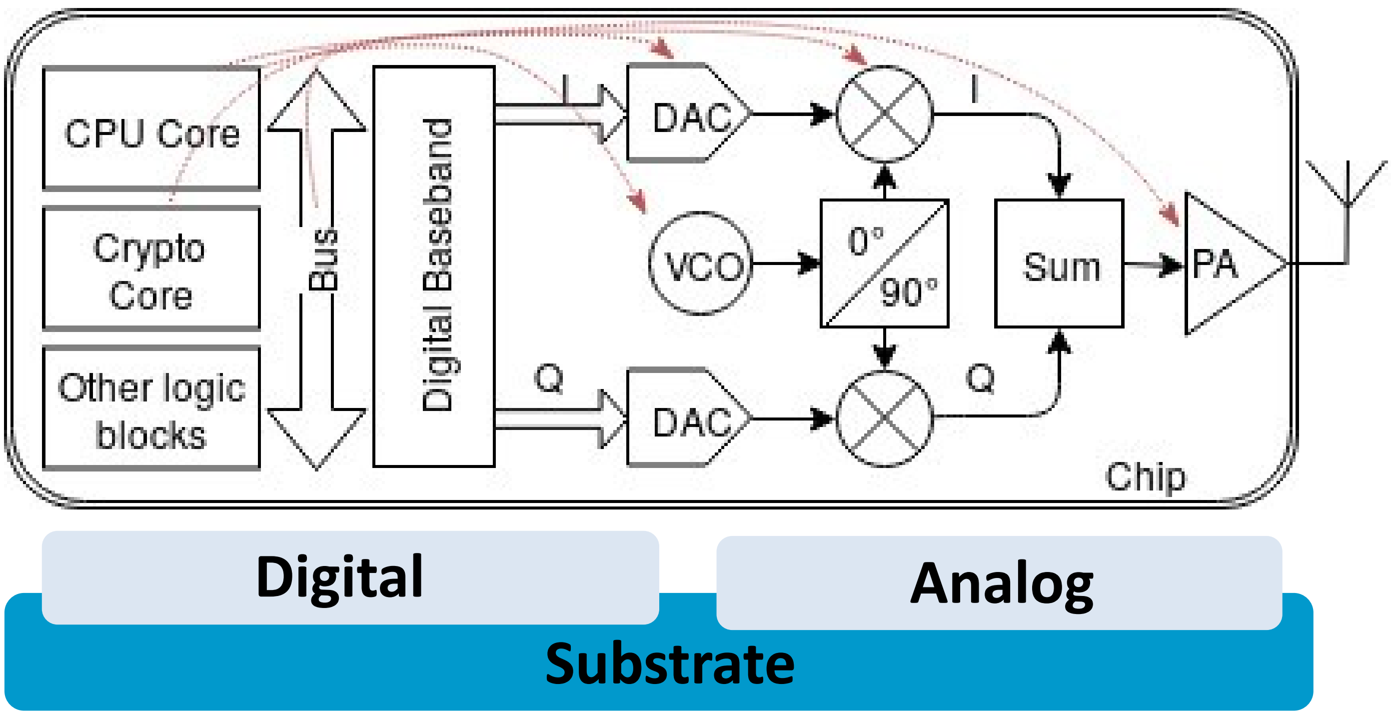


Screaming Channels: Leak Broadcast



From Digital Noise
To Noise On The Radio Signal

Possible Impact on Radio Transmission

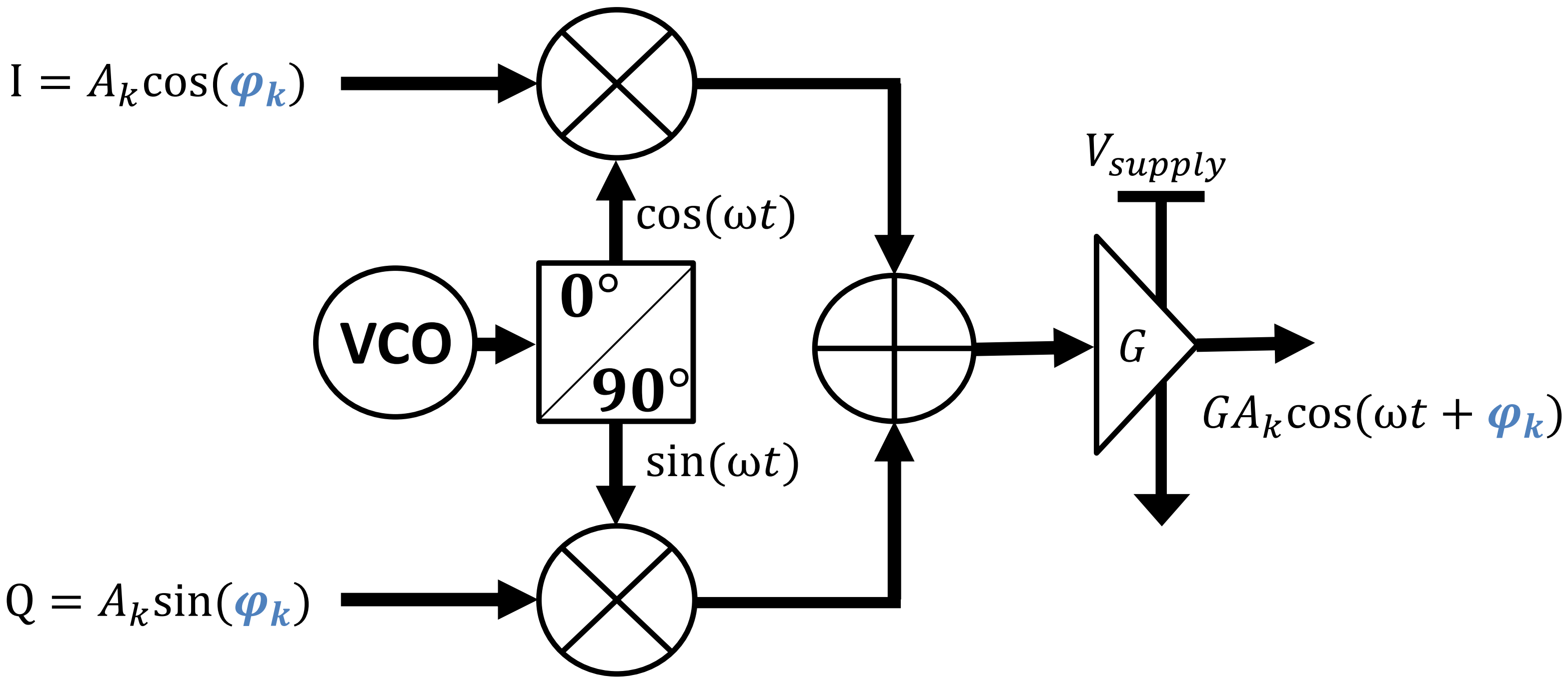


Digital: Inherently noisy

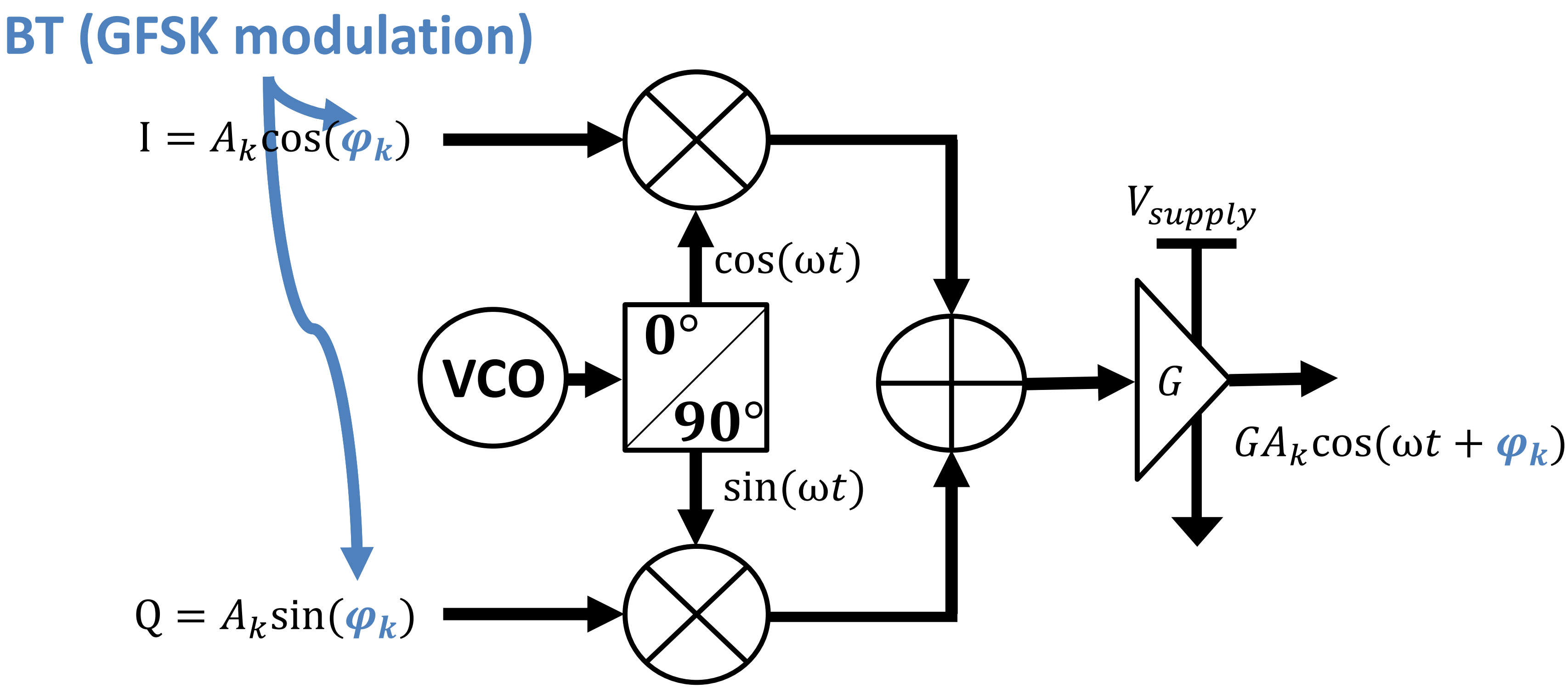
Propagation: Substrate coupling, Power supply/Gnd

Analog: Noise sensitive

Practical Case We Observed



Practical Case We Observed



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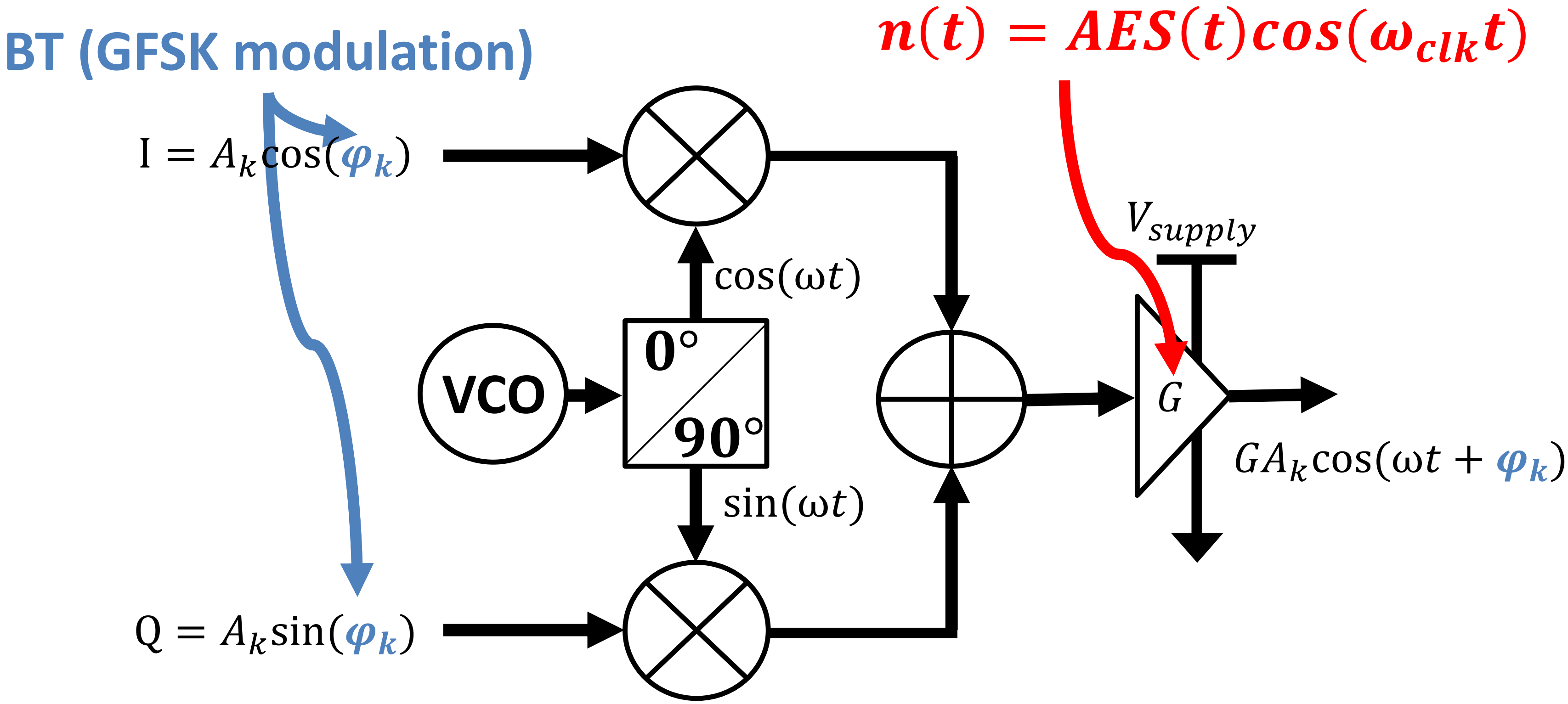
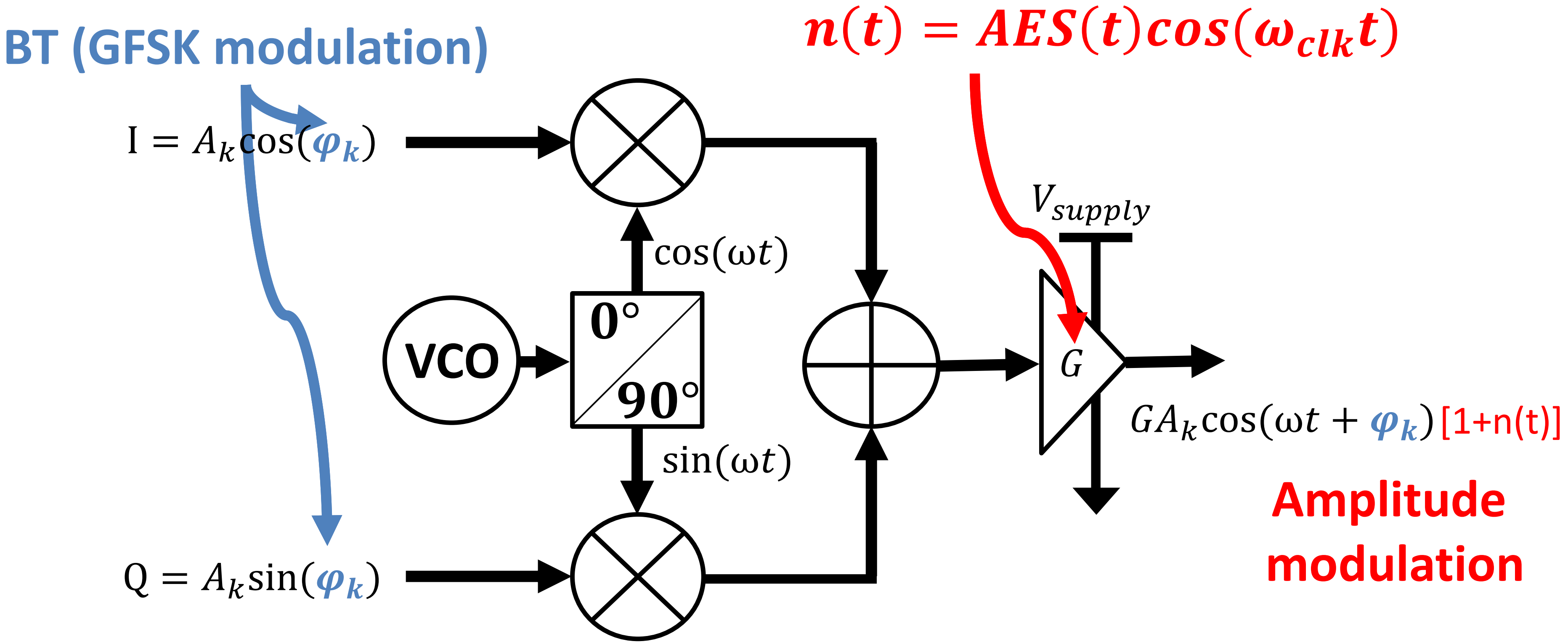


Practical Case We Observed



Extraction

Quadrature Amplitude Demodulation

$$\frac{GA_k}{2} AES(t) \cos((\omega + \omega_{clk})t + \varphi_k)$$

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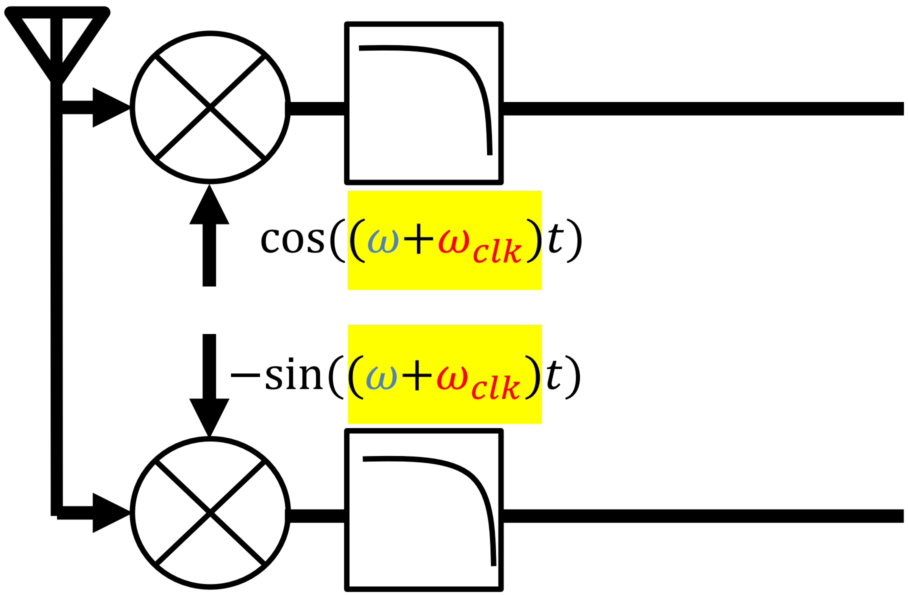

Quadrature Amplitude Demodulation

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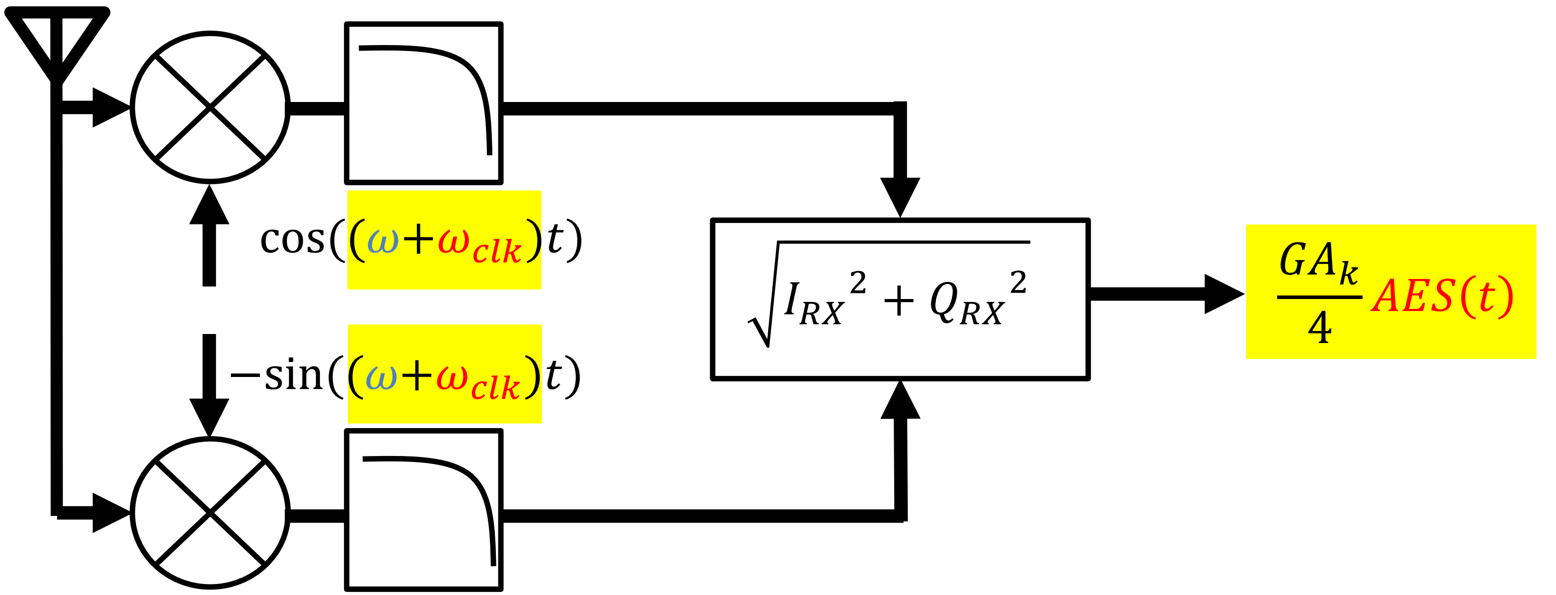
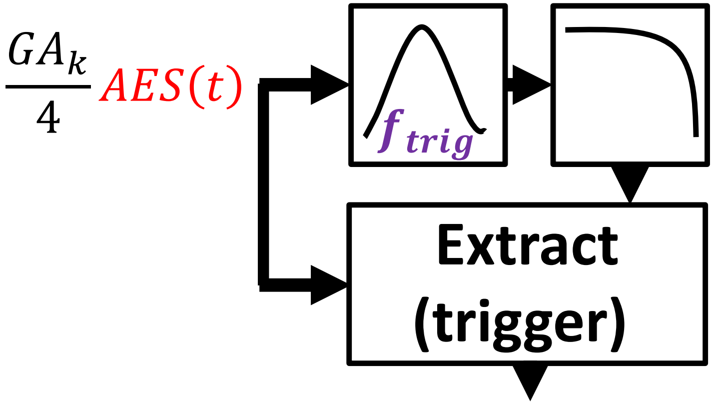


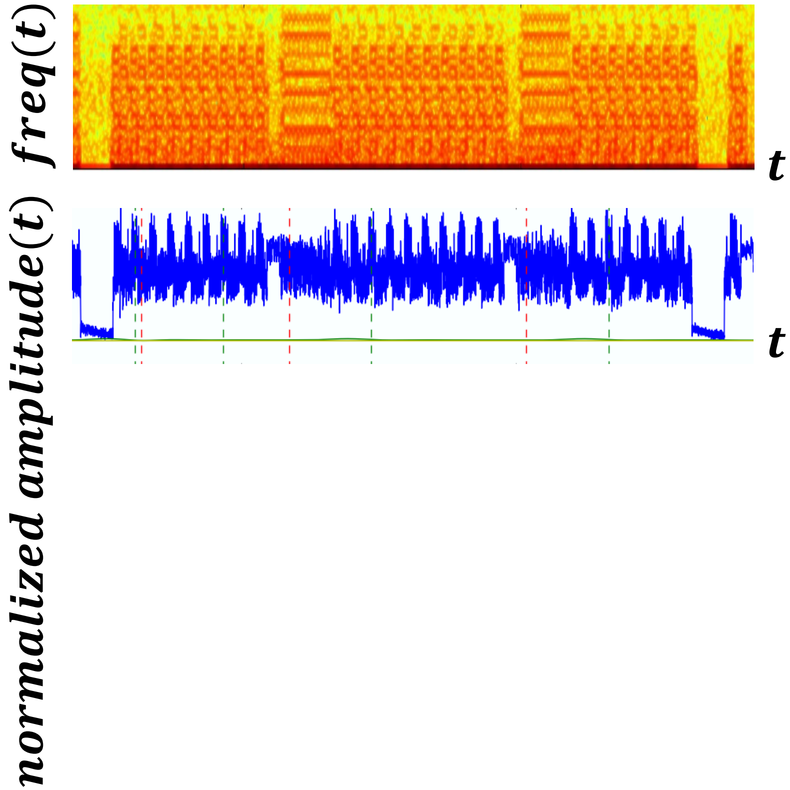
INSTITUT CARNOT Télécom & Société numérique

EURECOM Sophia Antipolis

Extraction

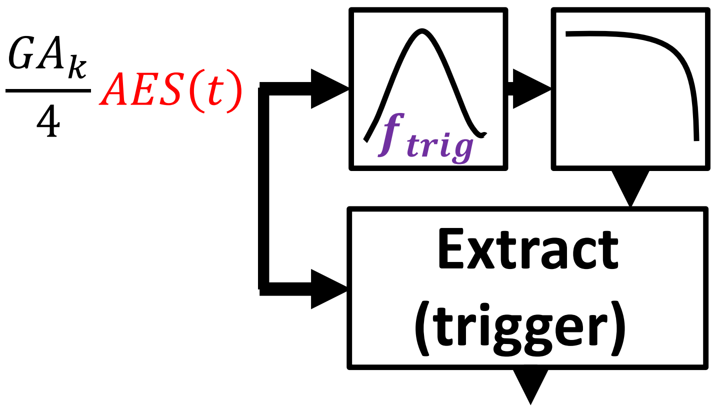


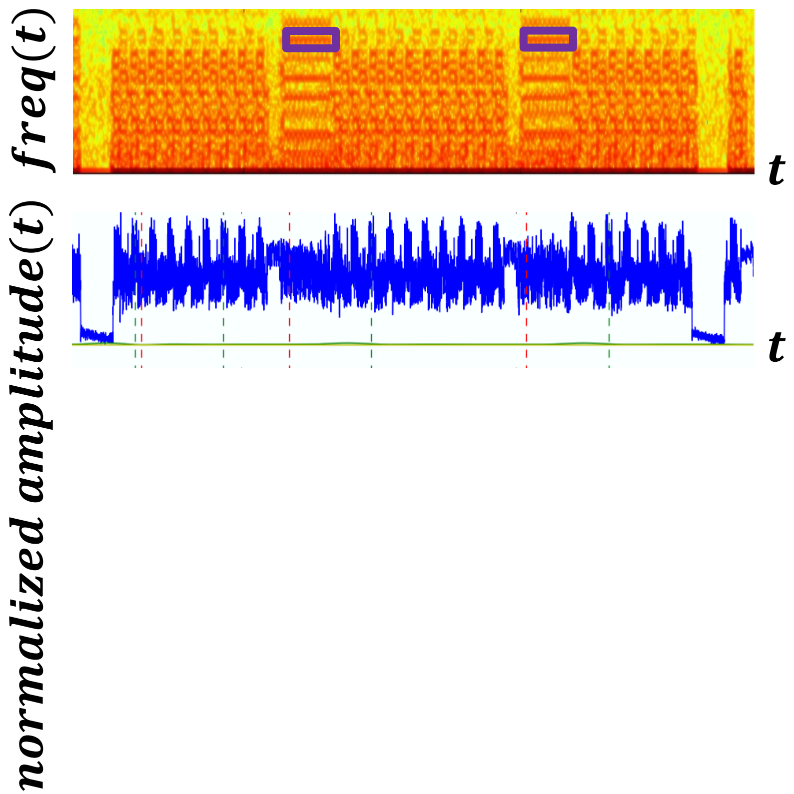
$\frac{GA_k}{4}AES(t)$
f_{trig}
Extract
(trigger)



$freq(t)$
t
$normalized\ amplitude(t)$
t

Extraction





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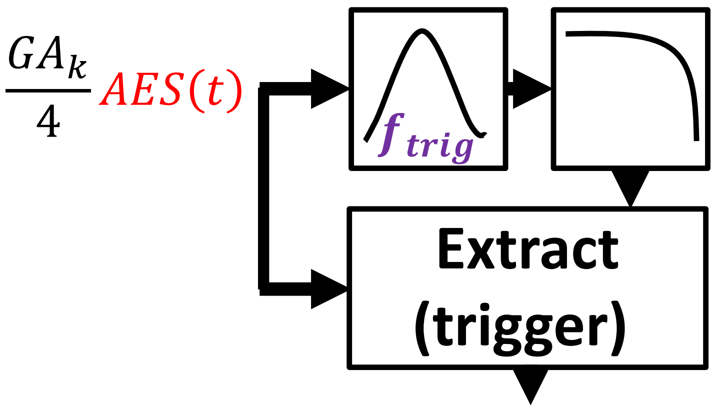
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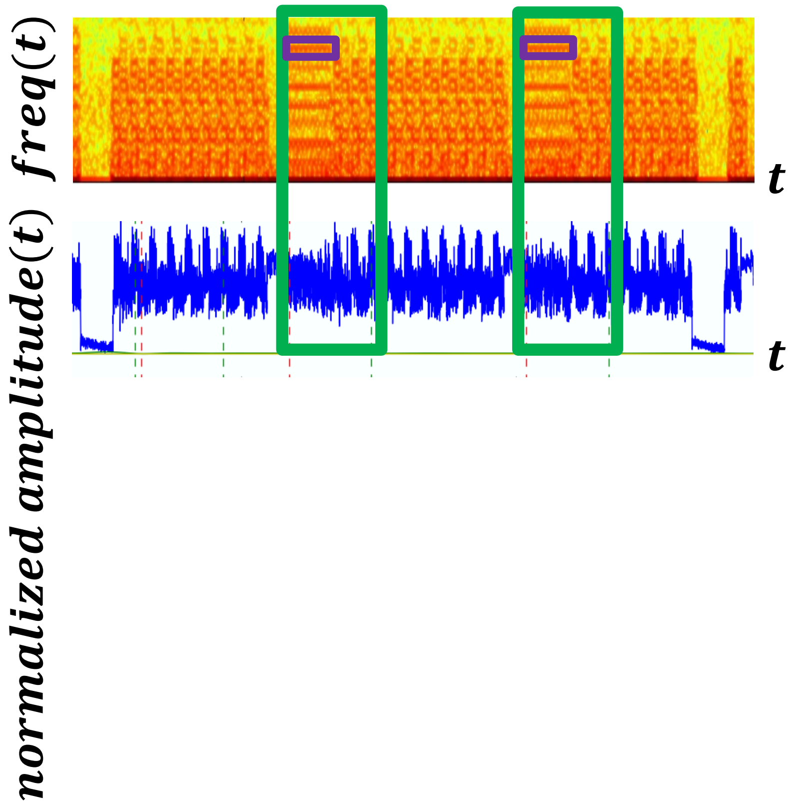
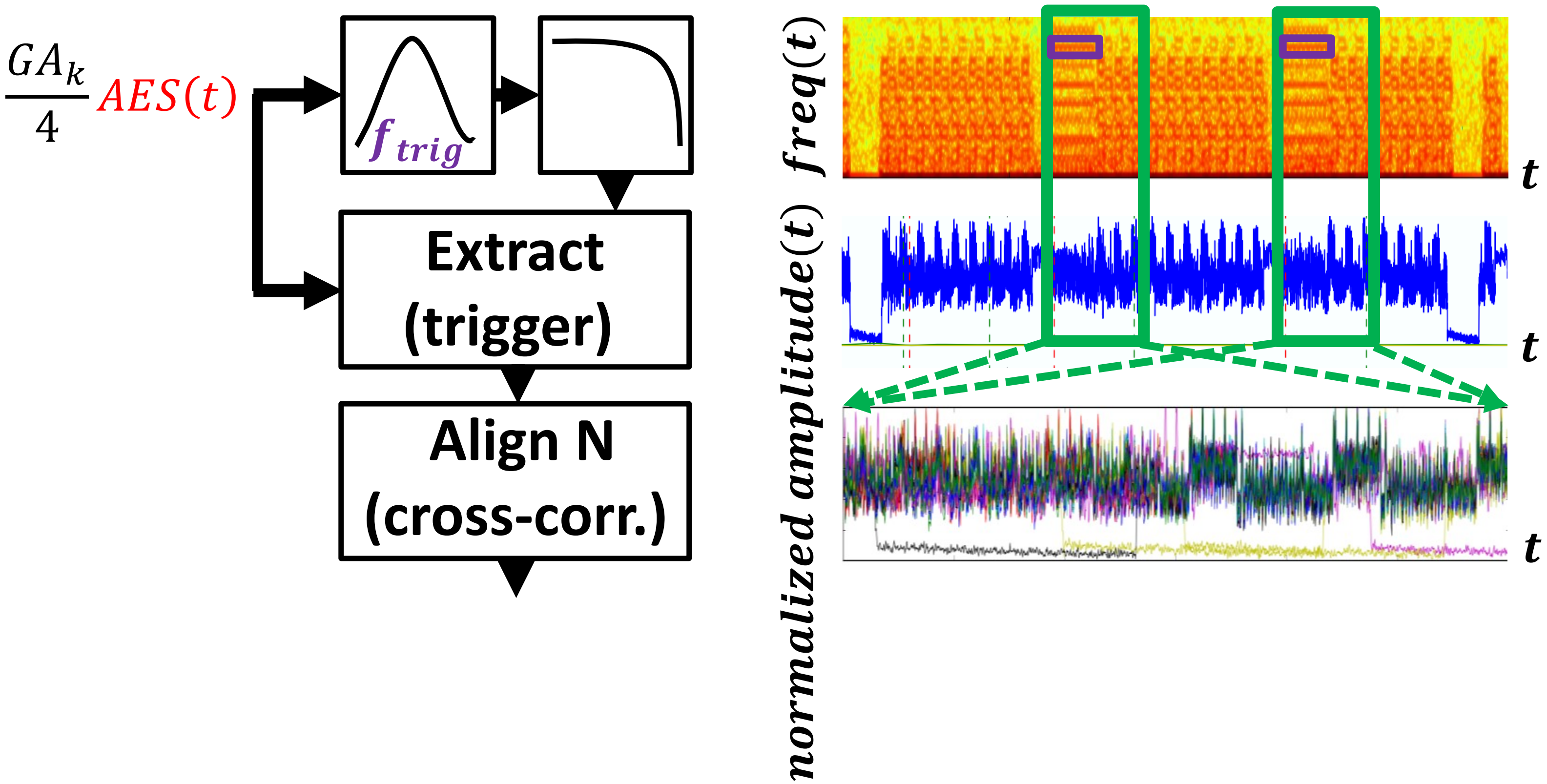
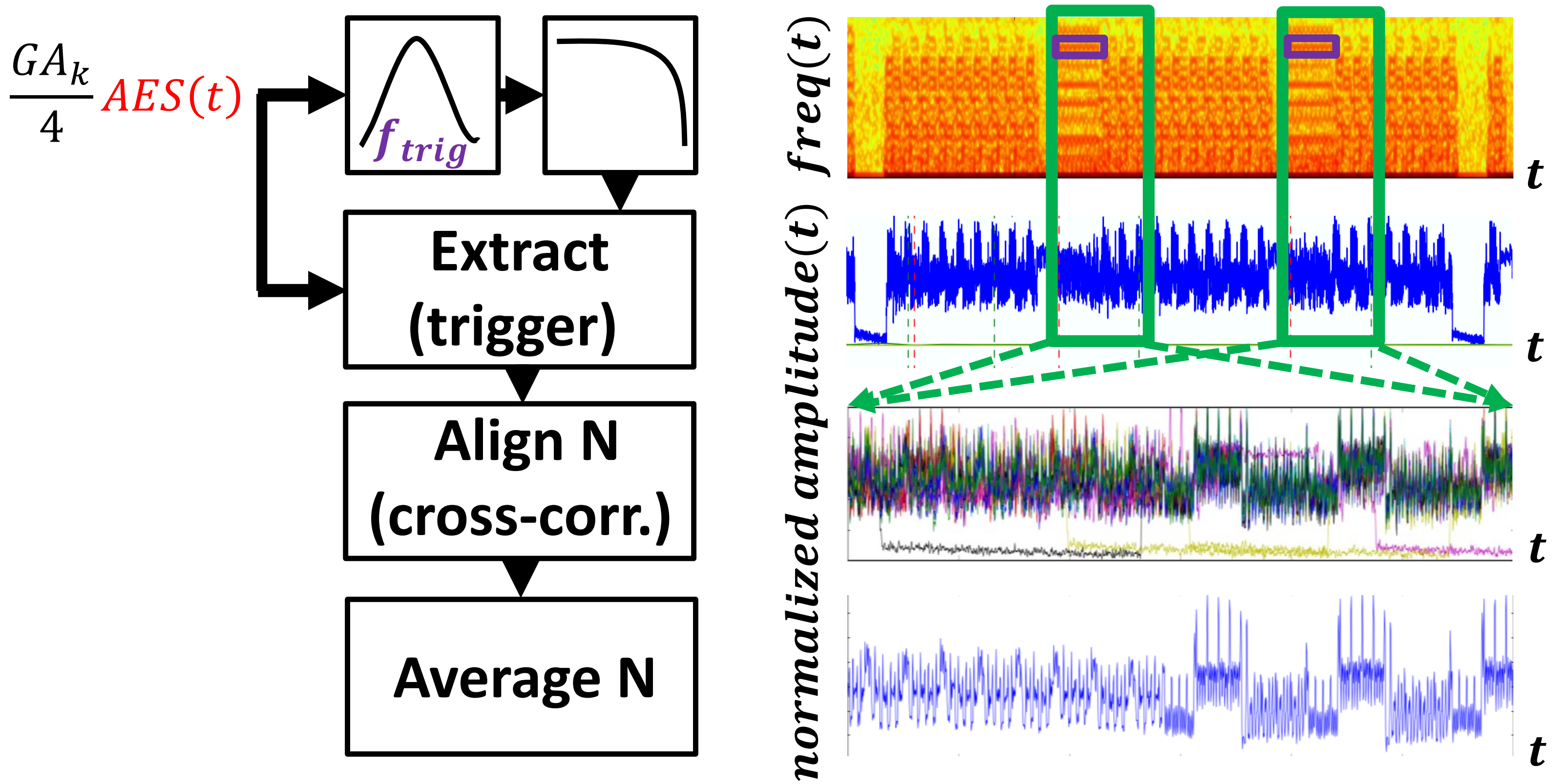

$freq(t)$
t
$normalized\ amplitude(t)$
t

Extraction



$\frac{GA_k}{4}AES(t)$
f_{trig}
Extract
(trigger)
Align N
(cross-corr.)
$freq(t)$
t
$normalized\ amplitude(t)$
t
t

Extraction



$\frac{GA_k}{4} AES(t)$
f_{trig}
Extract
(trigger)
Align N
(cross-corr.)
Average N
$freq(t)$
$normalized\ amplitude(t)$
t
t
t
t

Attack

Attacking

Targets:
Cortex-M4 + BT TX
TinyAES, mbedTLS

Attacking

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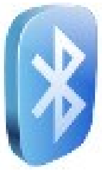

Extraction:
Automated via radio
Known plaintext

Attacking

Targets:
Cortex-M4 + BT TX
TinyAES, mbedTLS

Extraction:
Automated via radio
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Attacks:
Correlation, Template
Code based on
ChipWhisperer

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Targets:
Cortex-M4 + BT TX
TinyAES, mbedTLS

Extraction:
Automated via radio
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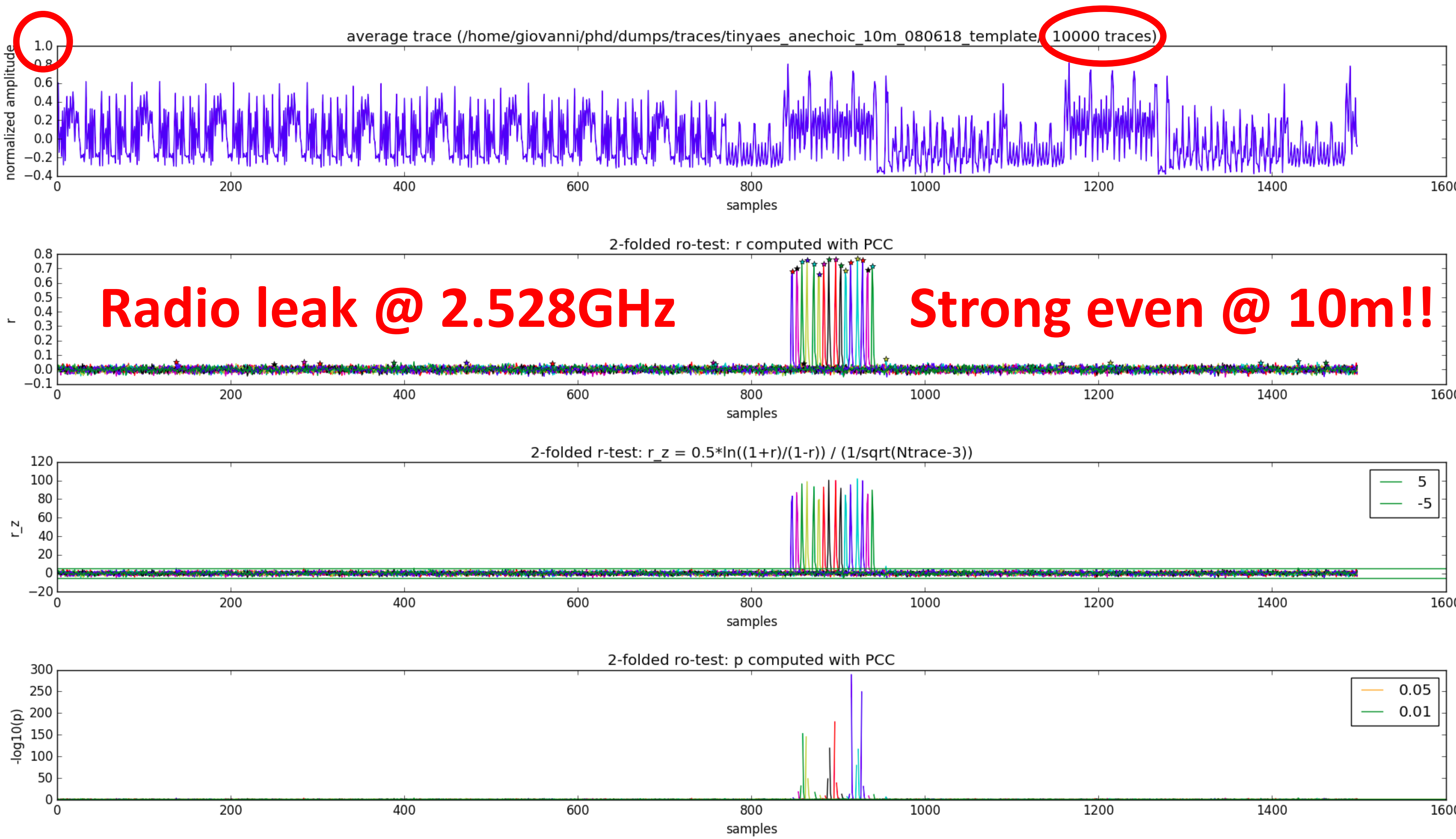
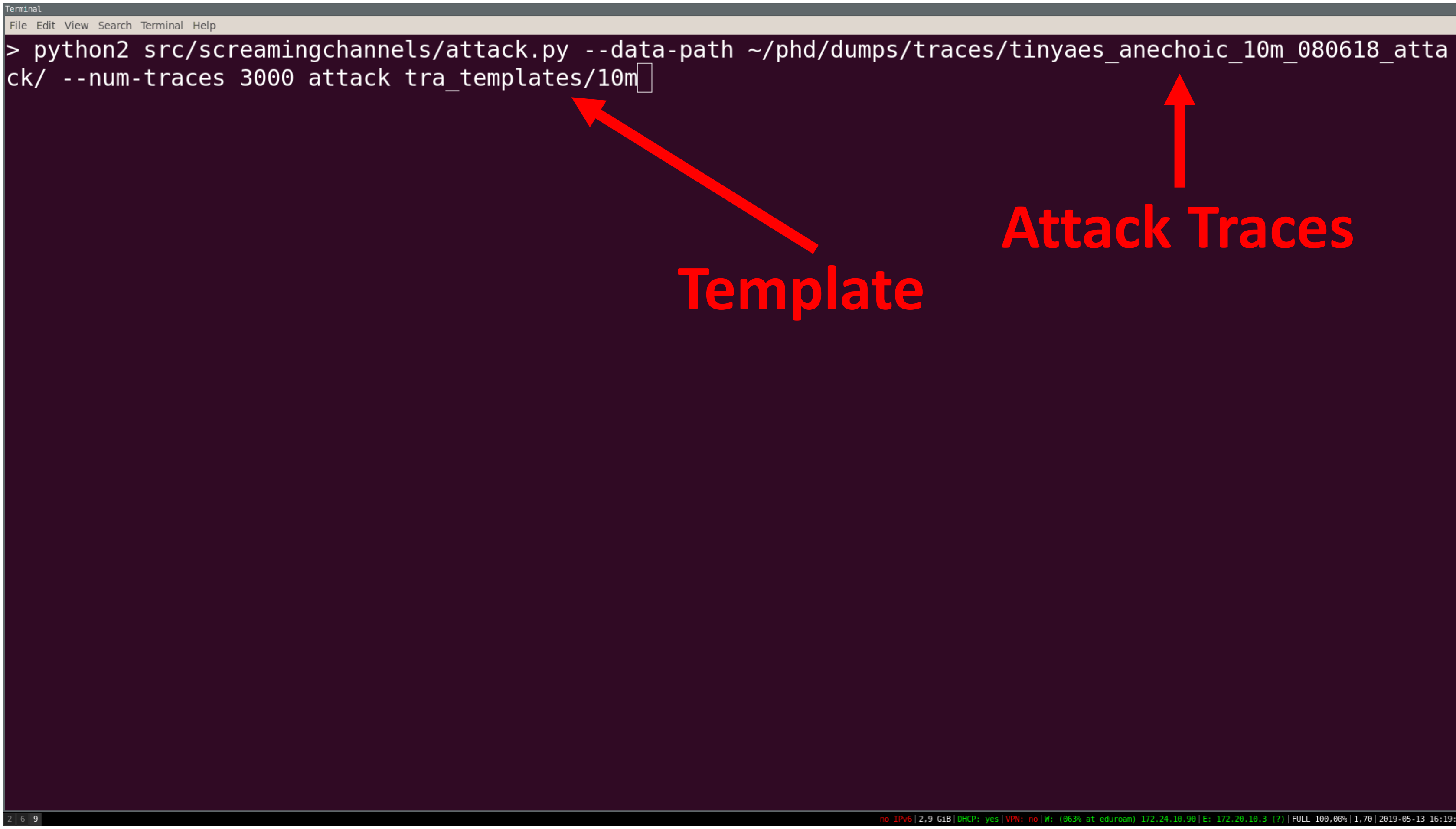
Attacks:
Correlation, Template
Code based on
ChipWhisperer

Much more advanced attacks exist

Correlation @ 10m



Quick Demo


Terminal
File Edit View Search Terminal Help
> python2 src/screamingchannels/attack.py --data-path ~/phd/dumps/traces/tinyaes_anechoic_10m_080618_attack/ --num-traces 3000 attack tra_templates/10m
Attack Traces
Template

Quick Demo

Terminal
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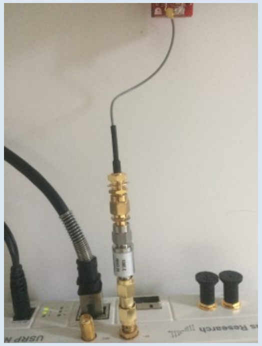
> python2 src/screamingchannels/attack.py --data-path ~/phd/dumps/traces/tinyaes_anechoic_10m_080618_attack/ --num-traces 3000 attack tra_templates/10m
Attack Traces
Template
Attack one byte
at a time

Quick Demo


Terminal
File Edit View Search Terminal Help
> python2 src/screamingchannels/attack.py --data-path ~/phd/dumps/traces/tinyaes_anechoic_10m_080618_attack/ --num-traces 3000 attack tra_templates/10m
Attack Traces
Template
Attack one byte at a time
SUCCESS!

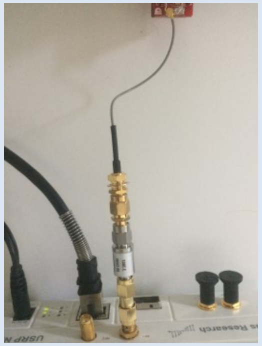
Evolution of the attack

Evolution of the attack

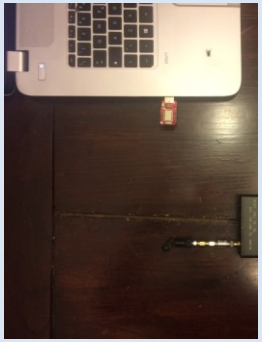


Cable

Evolution of the attack

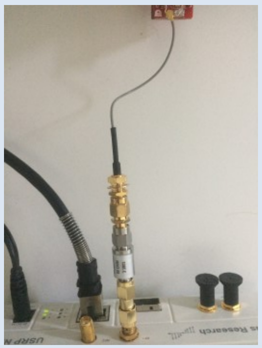


$\boldsymbol{Cable}$

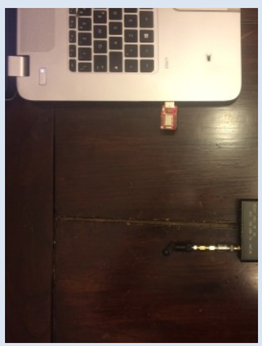


$\boldsymbol{15\ cm}$

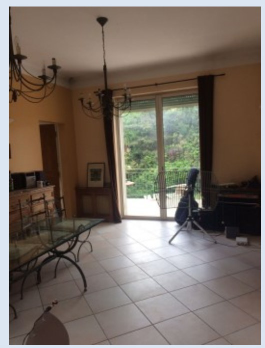
Evolution of the attack



$\boldsymbol{Cable}$

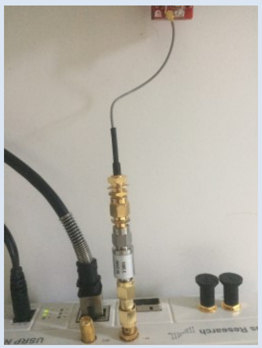


$\boldsymbol{15\ cm}$

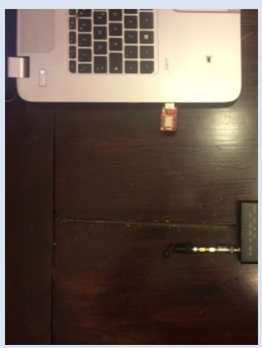


$\boldsymbol{2\ m}$

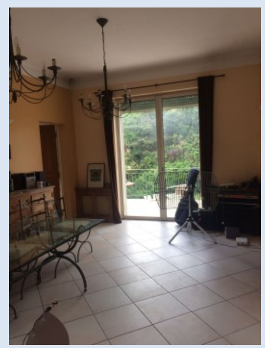
Evolution of the attack



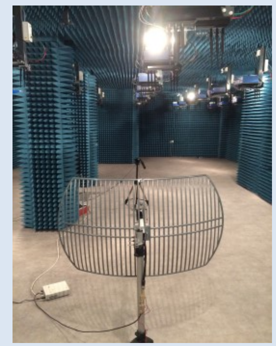
Cable



15 ***cm***

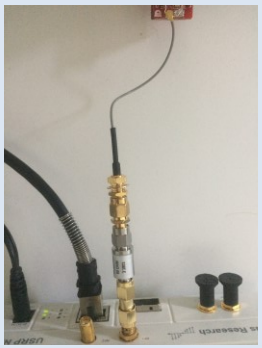


2 ***m***

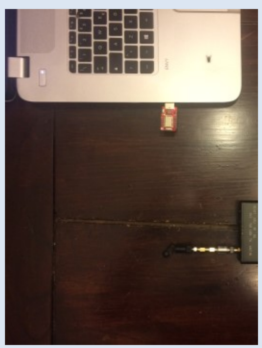


3 ***m***

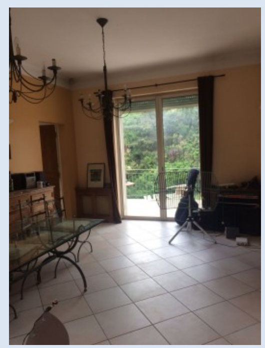
Evolution of the attack



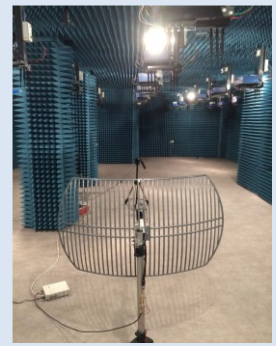
Cable



15 *cm*



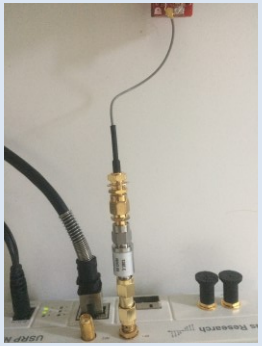
2 *m*



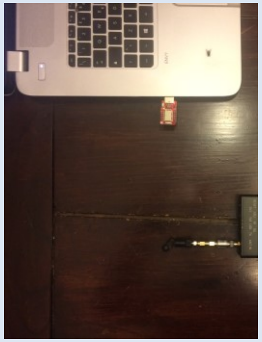
3 *m*

5 *m*

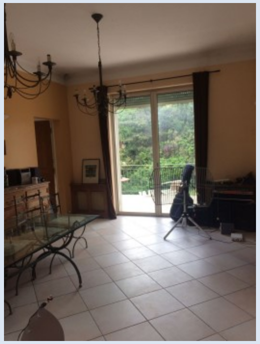
Evolution of the attack



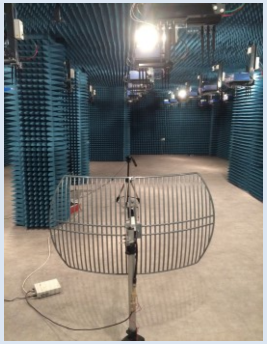
Cable



15 cm

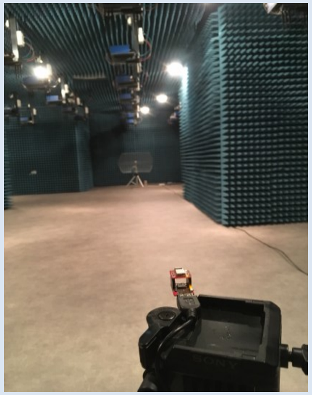


2 m



3 m

5 m



10 m

Protection

Countermeasures

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

Countermeasures

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Classic HW/SW:
Masking, noise, key refresh (expensive, not complete)

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Specific (SW):
Radio off during sensitive computations (real time constraints)

Countermeasures

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Cost, power, time to market, etc.

Classic HW/SW:
Masking, noise, key refresh (expensive, not complete)

Specific (SW):
Radio off during sensitive computations (real time constraints)

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

Final remarks

Reference to a Similar Effect

1-5. (~~C~~) Propagation of TEMPEST Signals (U). - There are four basic means by which compromising emanations may be propagated. They are: electromagnetic radiation; conduction; modulation of an intended signal; and acoustics. A brief explanation of each follows.

a. (~~C~~) Electromagnetic Radiation (U). - Whenever a RED signal is generated or processed in an equipment, an electric, magnetic or electromagnetic field is generated. If this electromagnetic field is permitted to exist outside of an equipment, a twofold problem is created; first the electromagnetic field may be detected outside the Controlled Space (CS); second the electromagnetic field may couple onto BLACK lines connected to or located near the equipments, which exit the CS of the installation.

b. (~~C~~) Line Conduction. - Line Conduction is defined as the emanations produced on any external or interface line of an equipment, which, in any way, alters the signal on the external or interface lines. The external lines include signal lines, control and indicator lines, and a.c. and d.c. powerlines.

c. (~~C~~) Fortuitous Conduction. - Emanations in the form of signals propagated along any unintended conductor such as pipes, beams, wires, cables, conduits, ducts, etc.

d. (~~C~~) [Six lines redacted.]

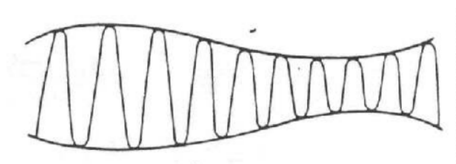

Figure 1-5. - Amplitude-Modulated Carrier (U) (U)

e. (~~C~~) Acoustics (U) - Characteristically plaintext processing systems are primarily electrical in function. However, other sources of CE exist where mechanical operations occur and sound is produced. Keyboards, printers, relays -- these produce sound. and consequently can be sources of compromise.

Propagation of leaks:

Tempest Fundamentals [5]
From ‘80s
Declassified 2000

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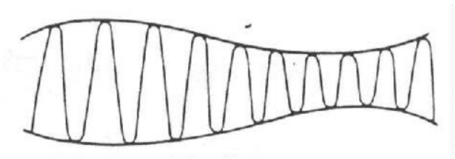

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Propagation of leaks:

1. Radiation

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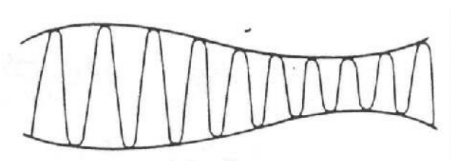

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Propagation of leaks:

1. **Radiation**
2. **Conduction**

Tempest Fundamentals [5]
From '80s
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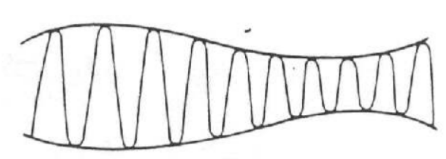

Figure 1-5. - Amplitude-Modulated Carrier (U) (U)

e. (~~C~~) Acoustics (U) - Characteristically plaintext processing systems are primarily electrical in function. However, other sources of CE exist where mechanical operations occur and sound is produced. Keyboards, printers, relays -- these produce sound. and consequently can be sources of compromise.

Propagation of leaks:

1. **Radiation**
2. **Conduction**

1. **Acoustic**

Tempest Fundamentals [5]

From ‘80s

Declassified 2000

Reference to a Similar Effect

1-5. (~~C~~) Propagation of TEMPEST Signals (U). - There are four basic means by which compromising emanations may be propagated. They are: electromagnetic radiation; conduction; modulation of an intended signal; and acoustics. A brief explanation of each follows.

a. (~~C~~) Electromagnetic Radiation (U). - Whenever a RED signal is generated or processed in an equipment, an electric, magnetic or electromagnetic field is generated. If this electromagnetic field is permitted to exist outside of an equipment, a twofold problem is created; first the electromagnetic field may be detected outside the Controlled Space (CS); second the electromagnetic field may couple onto BLACK lines connected to or located near the equipments, which exit the CS of the installation.

b. (~~C~~) Line Conduction. - Line Conduction is defined as the emanations produced on any external or interface line of an equipment, which, in any way, alters the signal on the external or interface lines. The external lines include signal lines, control and indicator lines, and a.c. and d.c. powerlines.

c. (~~C~~) Fortuitous Conduction. - Emanations in the form of signals propagated along any unintended conductor such as pipes, beams, wires, cables, conduits, ducts, etc.

d. (~~C~~) [Six lines redacted.]

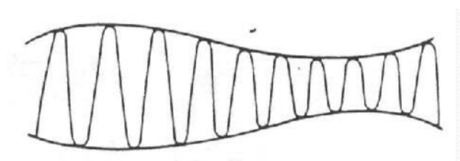

Figure 1-5. - Amplitude-Modulated Carrier (U) (U)

e. (~~C~~) Acoustics (U) - Characteristically plaintext processing systems are primarily electrical in function. However, other sources of CE exist where mechanical operations occur and sound is produced. Keyboards, printers, relays -- these produce sound. and consequently can be sources of compromise.

Propagation of leaks:

1. **Radiation**
2. **Conduction**
3. **Modulation of an intended signal (redacted)**
4. **Acoustic**

Tempest Fundamentals [5]
From '80s
Declassified 2000

Responsible Disclosure

Major vendors & multiple CERTS

Multiple acknowledgements of the relevance and generality of the problem

2 vendors are reproducing our results
1 vendor is actively looking at short/long-term countermeasures

Conclusion

General problem if sensitive processing and wireless tx

- **HW AES, WiFi, other chips**
- **any device with radio?**

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A new point in the threat model space

- **Remote EM attacks**

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Must be considered

- **Design and test of new devices**
- **Smart countermeasures (specific)**

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- **Remote EM attacks**

Must be considered

- **Design and test of new devices**
- **Smart countermeasures (specific)**

Many open directions for future research

- **More distant, less traces**
- **Different crypto and wireless technologies**
- **Attack the protocol**

Questions?

Code

https://www.github.com/eurecom-s3/screaming_channels

More Info

https://s3.eurecom.fr/tools/screaming_channels

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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

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