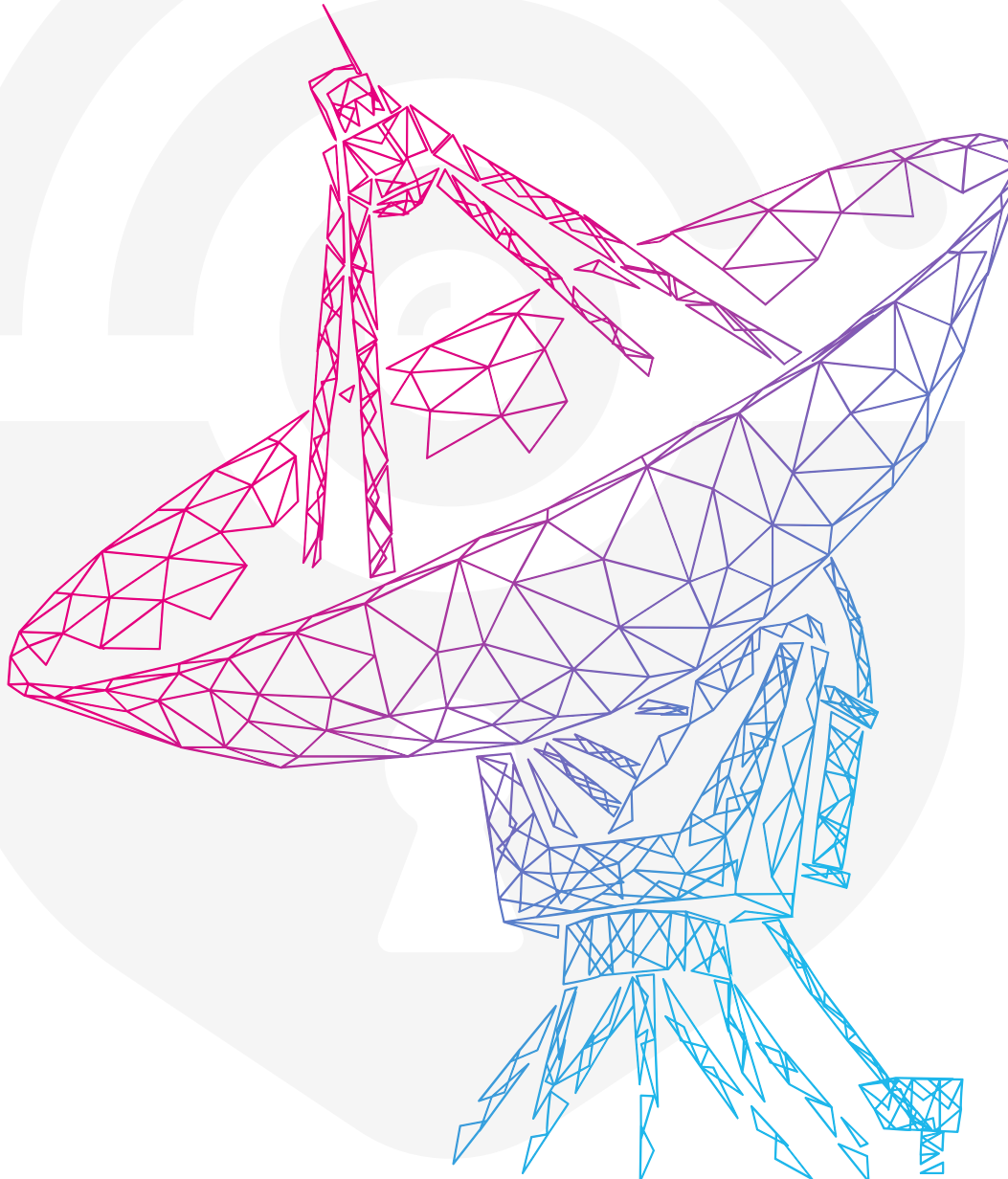
penthertz

RF Signal Hunting

With the help of ML and DL



Founder of Penthertz

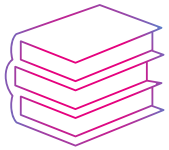
- Sébastien Dudek (@FlUxIuS)
- > 10 years of experience in Software / Hardware security
  - Former Sogeti ESEC R&D as a researcher
  - and Synacktiv as a pentester + vulnerabilities researcher
- Specialized in Wireless communications
- Also, security researcher @Trend Micro
  - Industrial IoT
  - Mobile and other RF/SDR things…

TREND MICRO | research

Main activities

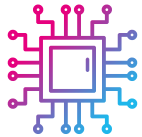
Security assessments

- Wireless communications (RFID, Wi-Fi, Mobile communication, Bluetooth, etc.)
- Embedded devices
- Backend servers
- Red Team



Trainings

- Software-Defined Radio Hacking
- Wi-Fi Red teaming
- RFID Hacking
- Mobile attacks (2G/3G/4G/5G)



Hardware security

- Firmware extraction
- Chip-off
- Secrets extraction
- Libraries analysis
- Vulnerability hunting

Part of our RF lab (wow clean desk)

RF Signal

“

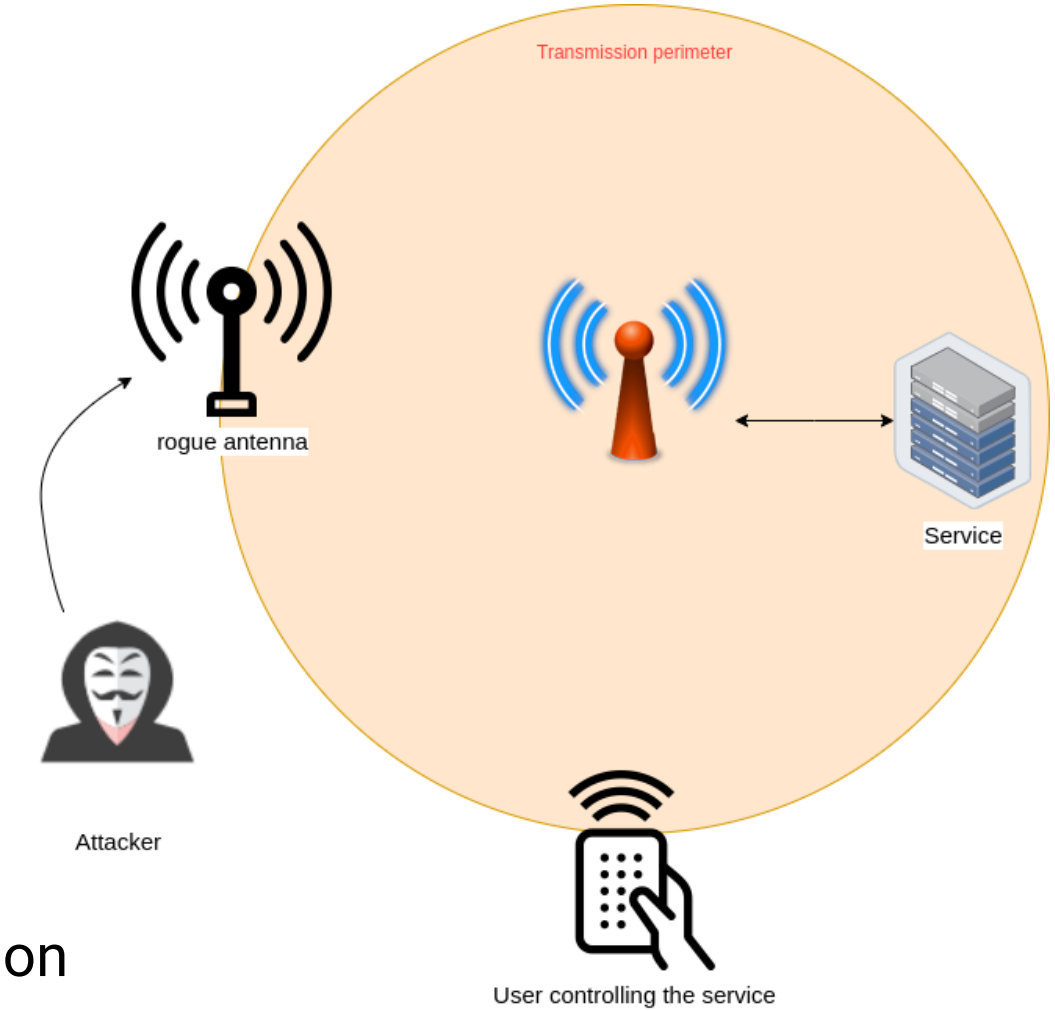
We just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there.

Heinrich Hertz

Risks OTA

Common vulnerabilities:

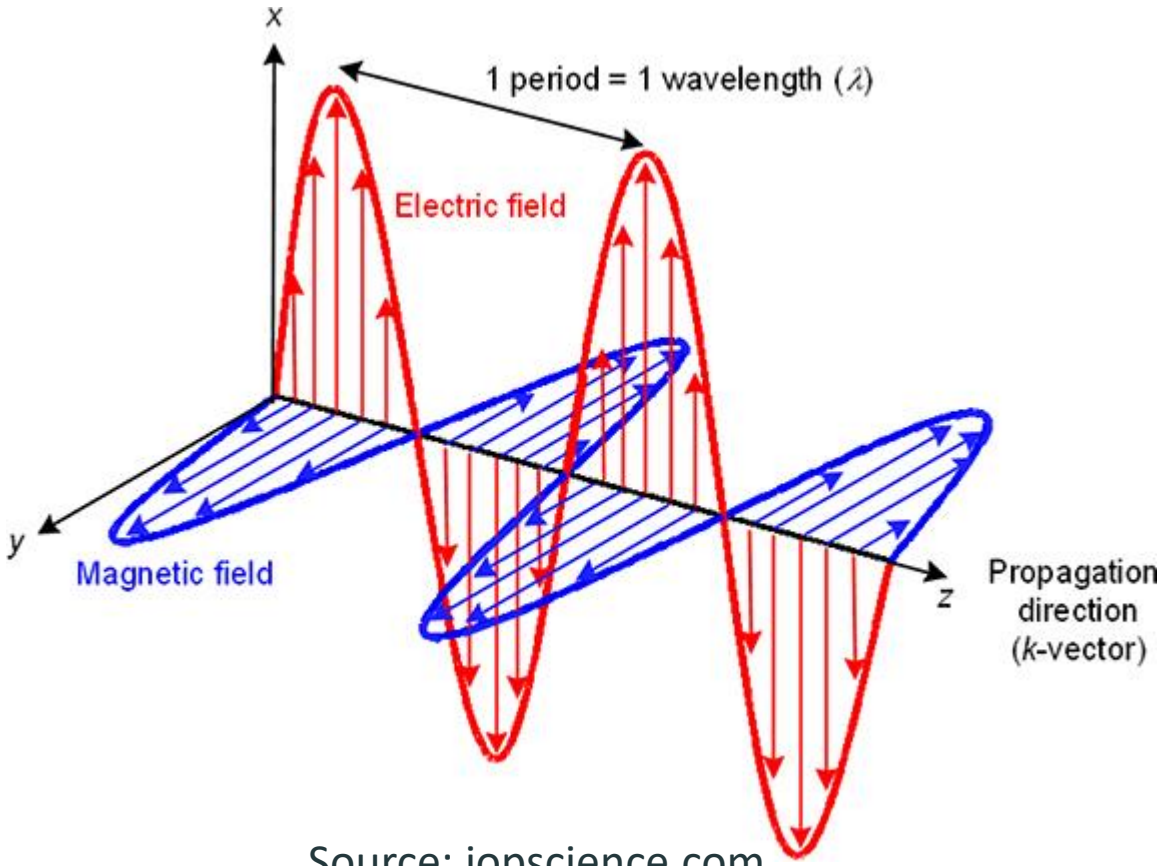
- Eavesdropping
- Replay
- Injection
- Relay
- Jamming
- DoS via (very) high amplitude transmission
- etc.



Radio wave characteristics

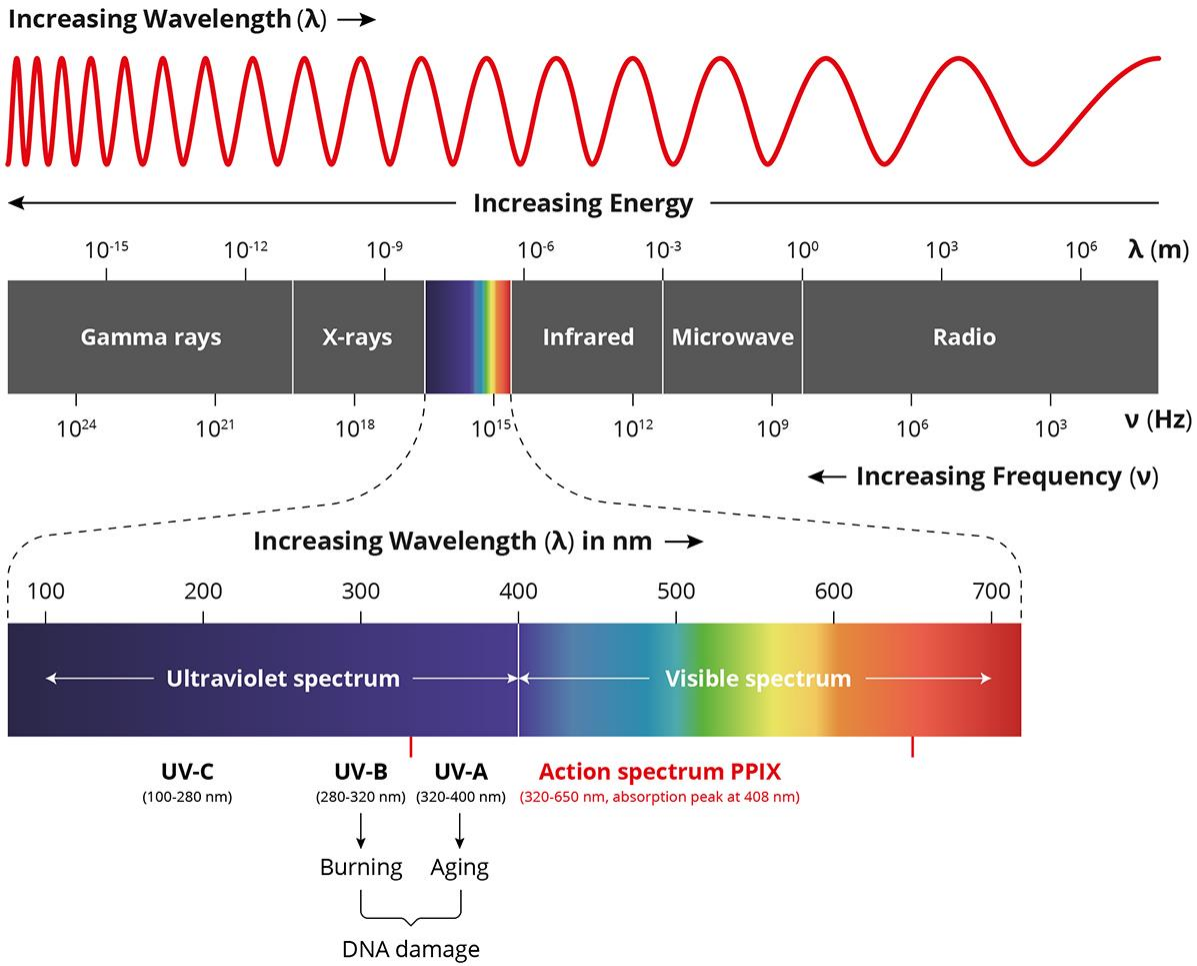
Important:

- λ: wavelength in meter
- c: celerity of light (3.108 $m.s^{-1}$)
- T: the period in seconds ($\frac{\lambda}{c}$)
- f: frequency in Hz ($\frac{1}{T}$)



Source: iopscience.com

Wave regions



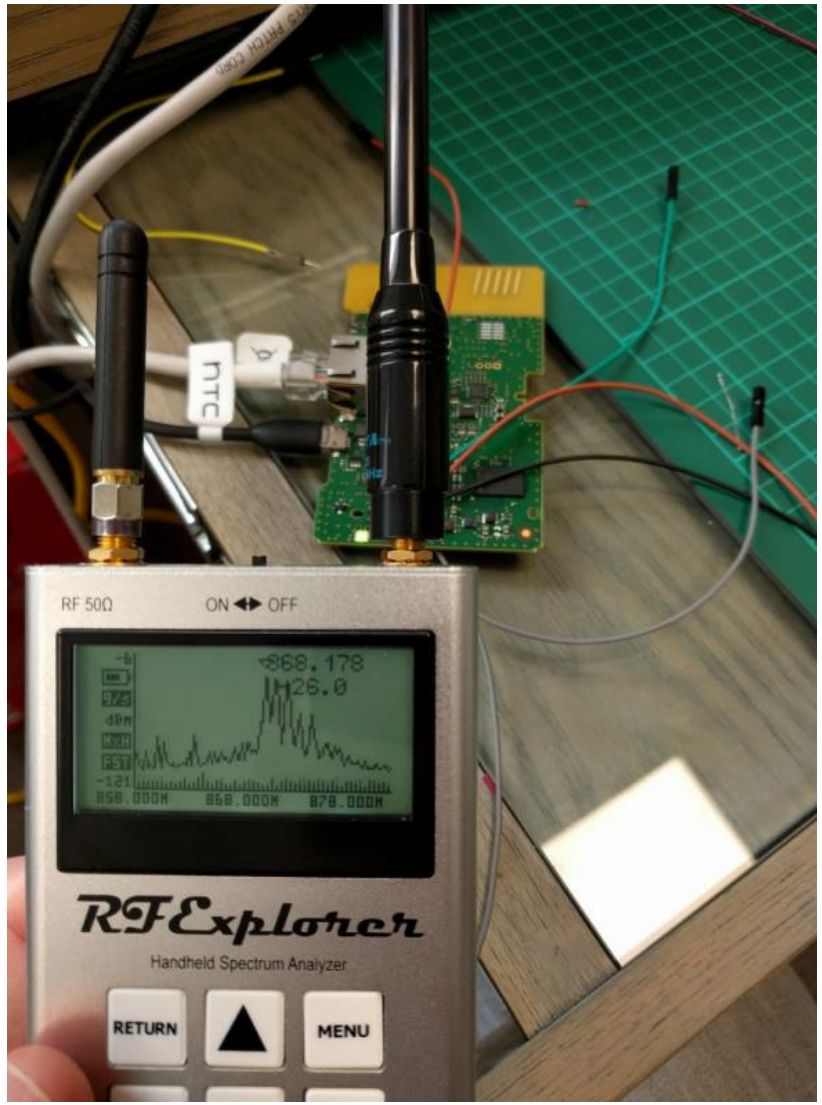
Identification

Spectrum analyzers

- A starting beast:
  - R&S® FSV40
  - 10 Hz to 40 GHz freq band
  - 160 MHz signal analysis bandwidth
  - costs > 43 000€

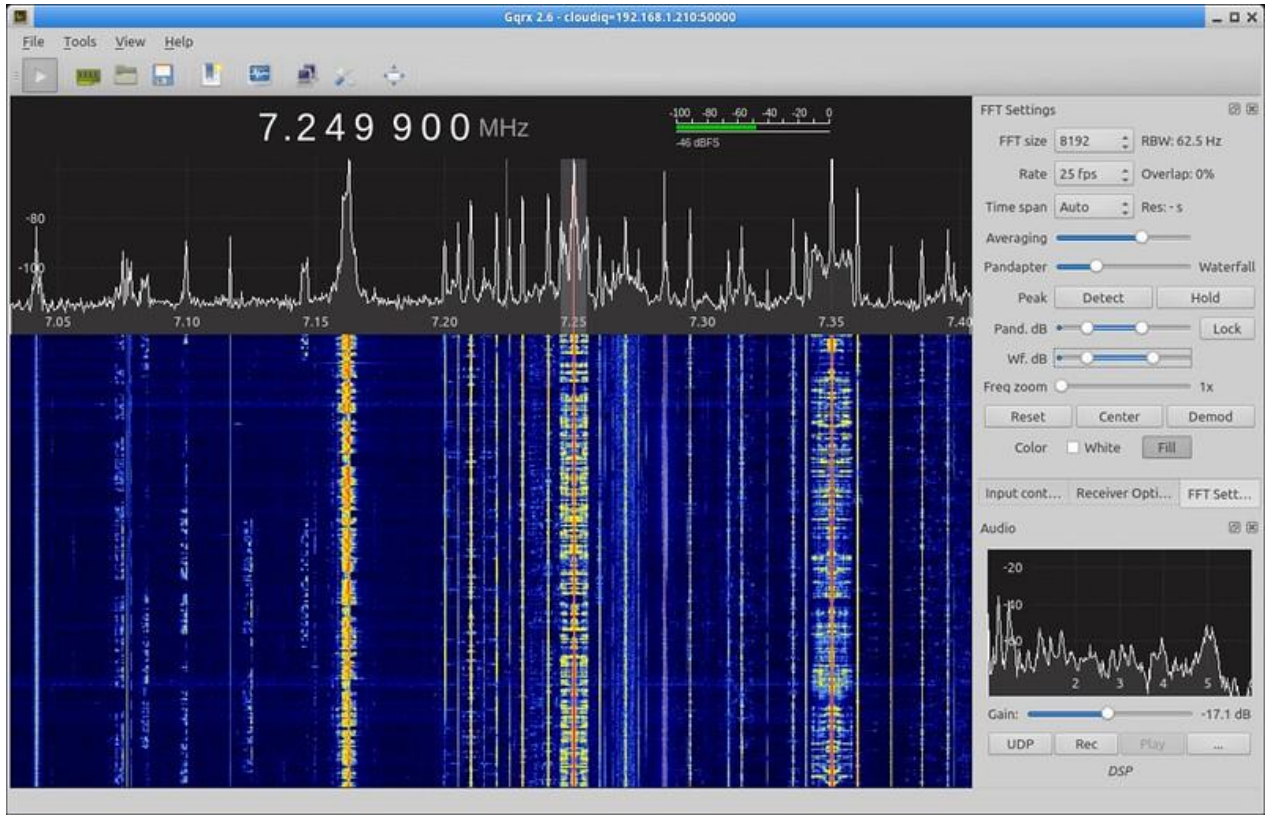
RF Explorer

- A handy gadget for < 300€:
  - Left SMA port (WSUB1G): 240-960MHz
  - Right SMA port (WSUB3G): 15-2700 MHz
  - Resolution bandwidth (RBW): automatic 3Khz to 600Khz



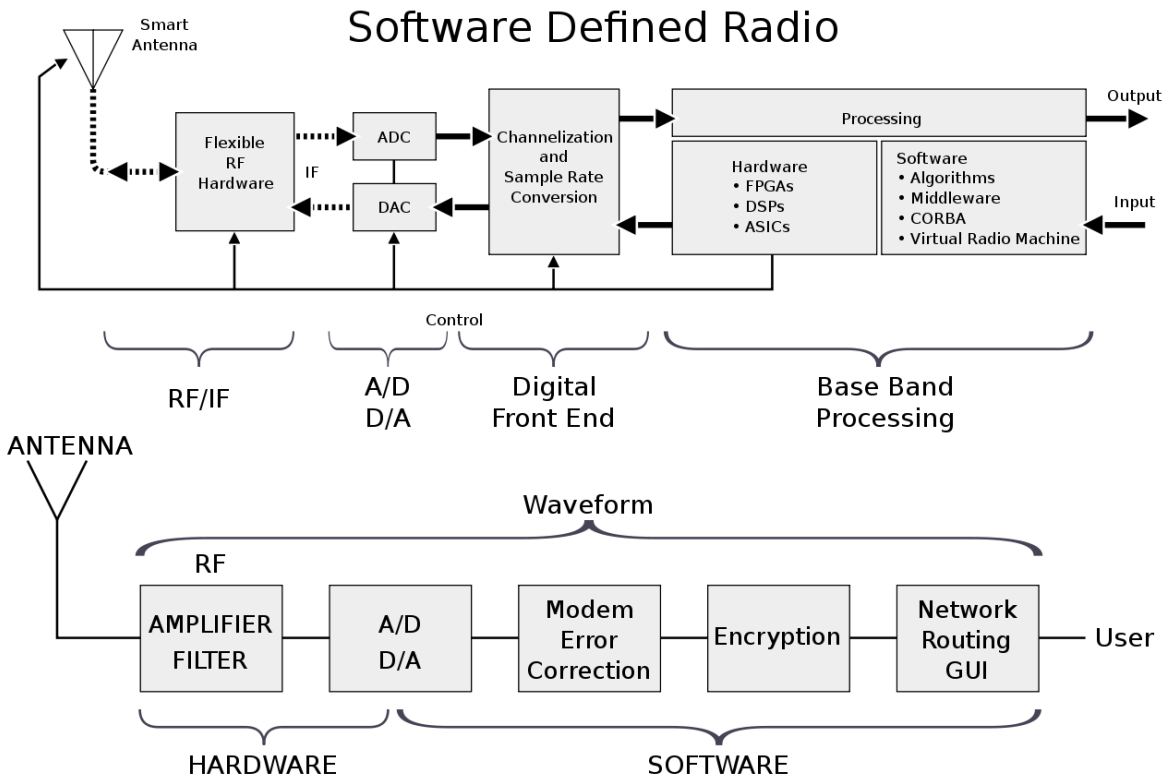
With SDR

- Famous software:
  - GQRX on Linux and Mac OS X
  - HDSDR on Windows
  - SDR# on Windows
  - SDR++ on Linux and Windows



Software-Defined Radio

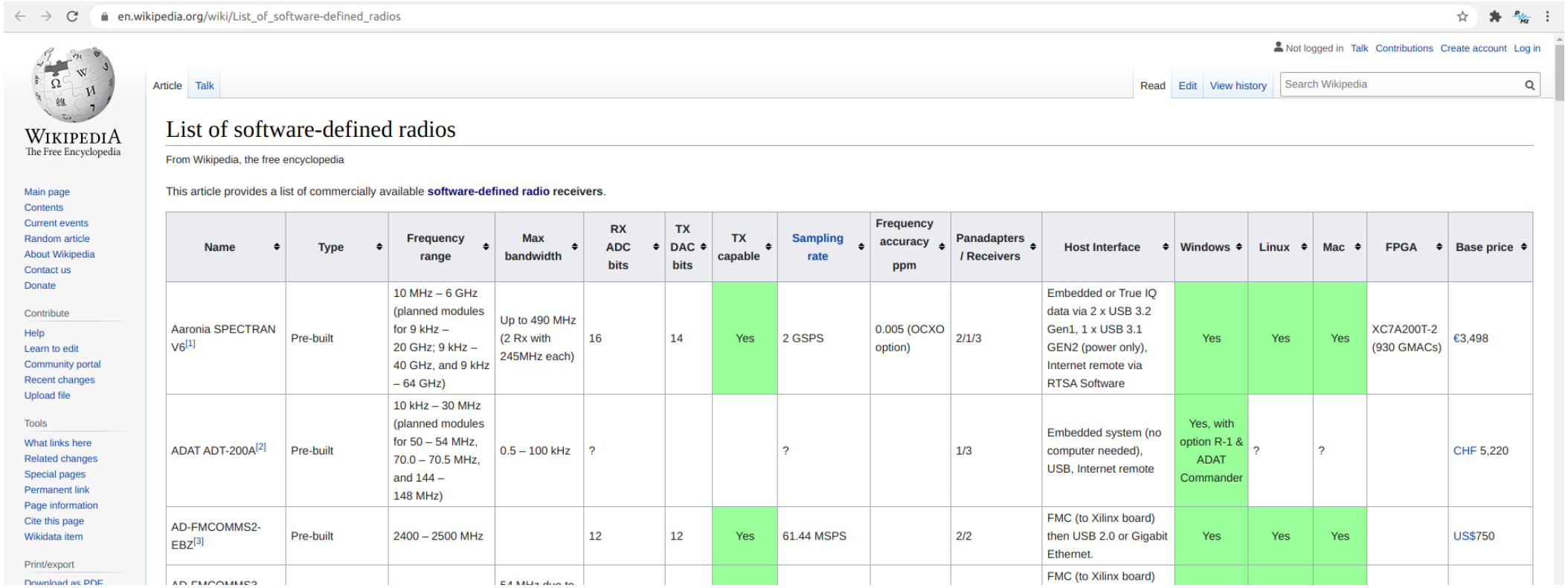
- Before SDR → difficult to get equipment without $$$
- Made radio more accessible
- Hardware:
  - Signal acquisition → IF;
  - ADC/DAC conversion;
  - RF Amp.;
  - and filtering.
- The rest is done in software
  - With your computer



Cheap SDR: RTL-SDR

- RTL-SDR
- Does only RX
- Different tuners/versions:
  - e.g. Elonics E4000 → 52-2200 MHz
- Costs from 15€
- RTL-SDR v3 is about 50€
- Good for a beginning

More than 100 SDR



en.wikipedia.org/wiki/List_of_software-defined_radios

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List of software-defined radios

From Wikipedia, the free encyclopedia

This article provides a list of commercially available **software-defined radio receivers**.

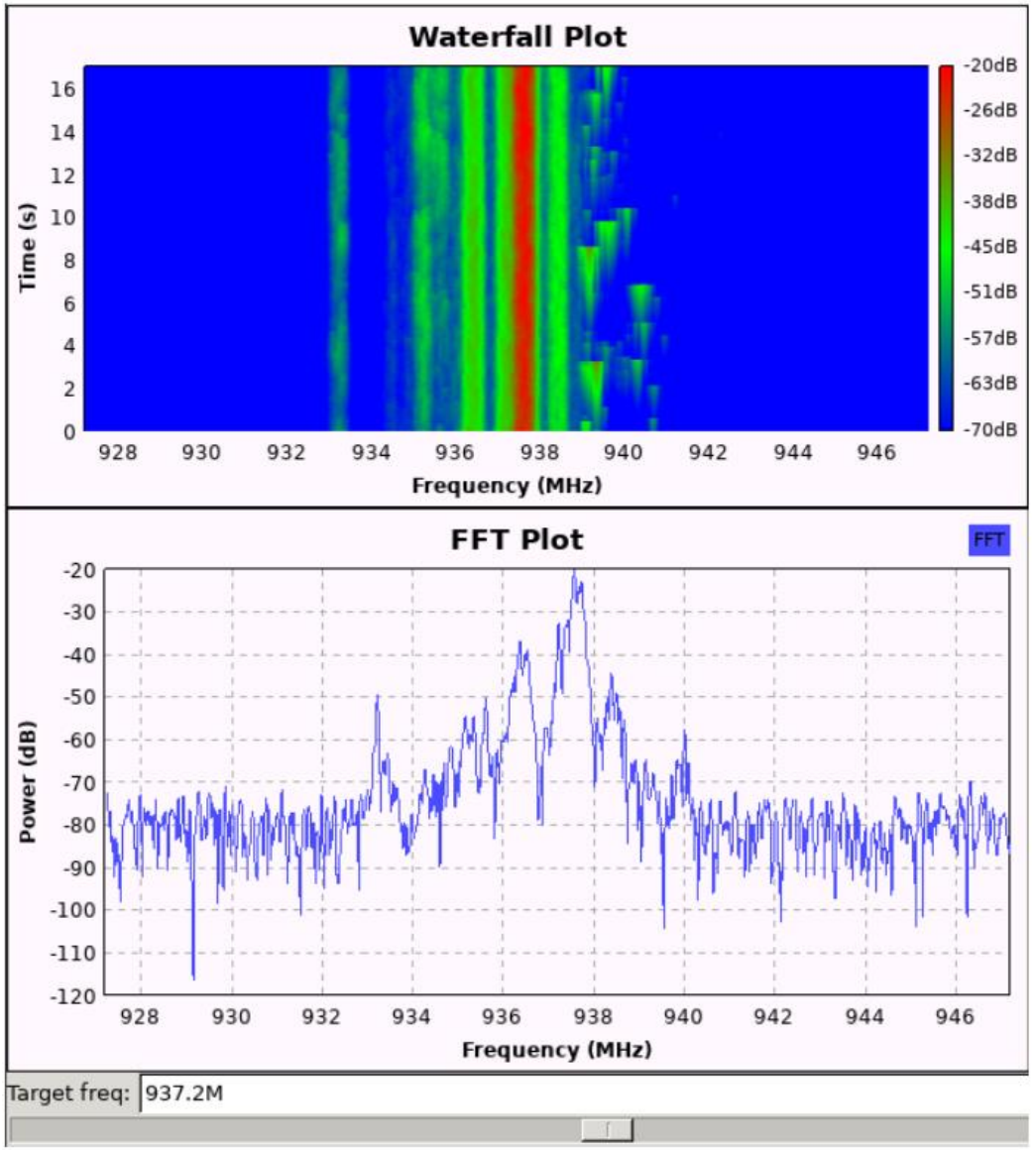
Name	Type	Frequency range	Max bandwidth	RX ADC bits	TX DAC bits	TX capable	Sampling rate	Frequency accuracy ppm	Panadapters / Receivers	Host Interface	Windows	Linux	Mac	FPGA	Base price
Aaronia SPECTRAN V6[1]	Pre-built	10 MHz – 6 GHz (planned modules for 9 kHz – 20 GHz; 9 kHz – 40 GHz, and 9 kHz – 64 GHz)	Up to 490 MHz (2 Rx with 245MHz each)	16	14	Yes	2 GSPS	0.005 (OCXO option)	2/1/3	Embedded or True IQ data via 2 x USB 3.2 Gen1, 1 x USB 3.1 GEN2 (power only), Internet remote via RTSA Software	Yes	Yes	Yes	XC7A200T-2 (930 GMACs)	€3,498
ADAT ADT-200A[2]	Pre-built	10 kHz – 30 MHz (planned modules for 50 – 54 MHz, 70.0 – 70.5 MHz, and 144 – 148 MHz)	0.5 – 100 kHz	?			?		1/3	Embedded system (no computer needed), USB, Internet remote	Yes, with option R-1 & ADAT Commander	?	?		CHF 5,220
AD-FMCOMMS2-EBZ[3]	Pre-built	2400 – 2500 MHz		12	12	Yes	61.44 MSPS		2/2	FMC (to Xilinx board) then USB 2.0 or Gigabit Ethernet.	Yes	Yes	Yes		US$750
AD-FMCOMMS3			54 MHz due to							FMC (to Xilinx board)					

A lot of characteristics to look at: TX/RX, full/half-duplex, max. samp. rate, clock stability, interface, freq range, software support, etc.

Issues

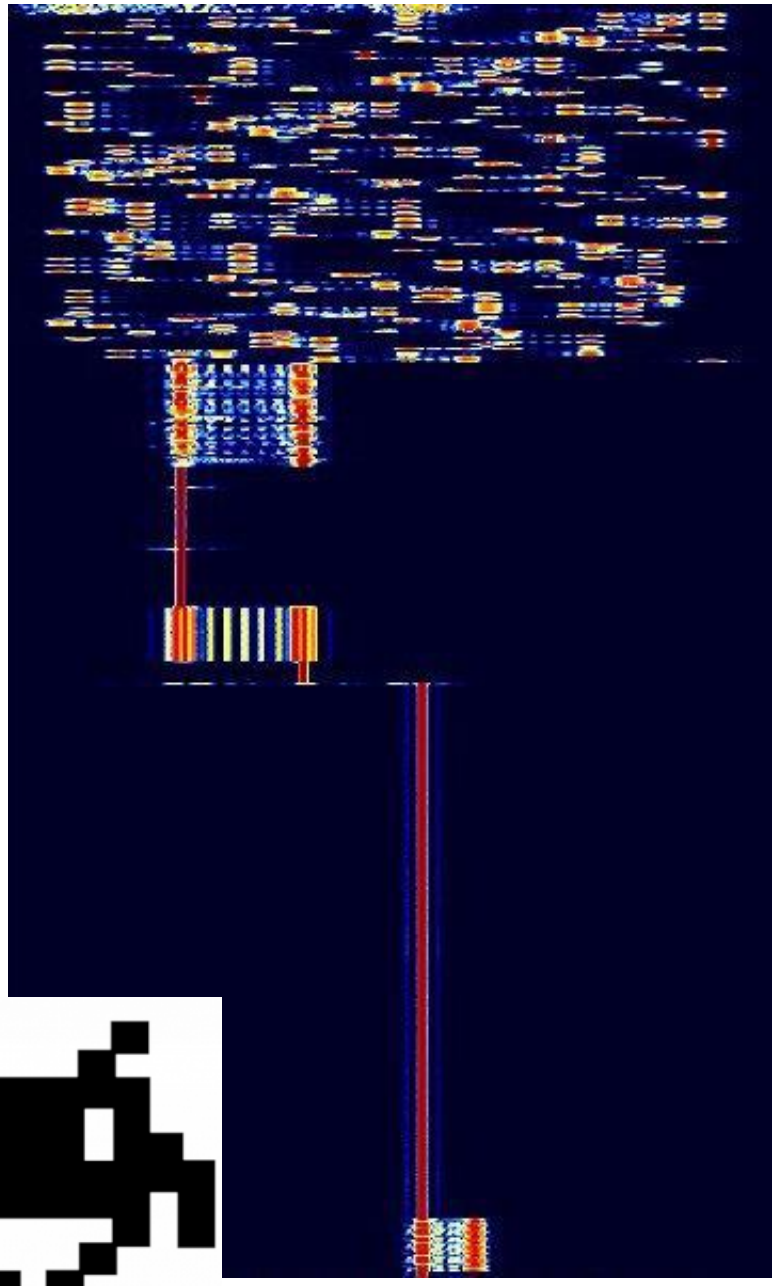
- How to identify the right technology?
  - Identify the frequency range
  - Used bandwidth
  - Duty cycle
  - Pattern
  - Other spectral properties
- But with what tools?

E.g.: FFT


Waterfall Plot
Time (s)
16
14
12
10
8
6
4
2
0
928
930
932
934
936
938
940
942
944
946
Frequency (MHz)
-20dB
-26dB
-32dB
-38dB
-45dB
-51dB
-57dB
-63dB
-70dB
FFT Plot
FFT
Power (dB)
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
928
930
932
934
936
938
940
942
944
946
Frequency (MHz)
Target freq:
937.2M

And then?

- We need a database:
  - Own collection
  - Public resources: like sigidwiki.com

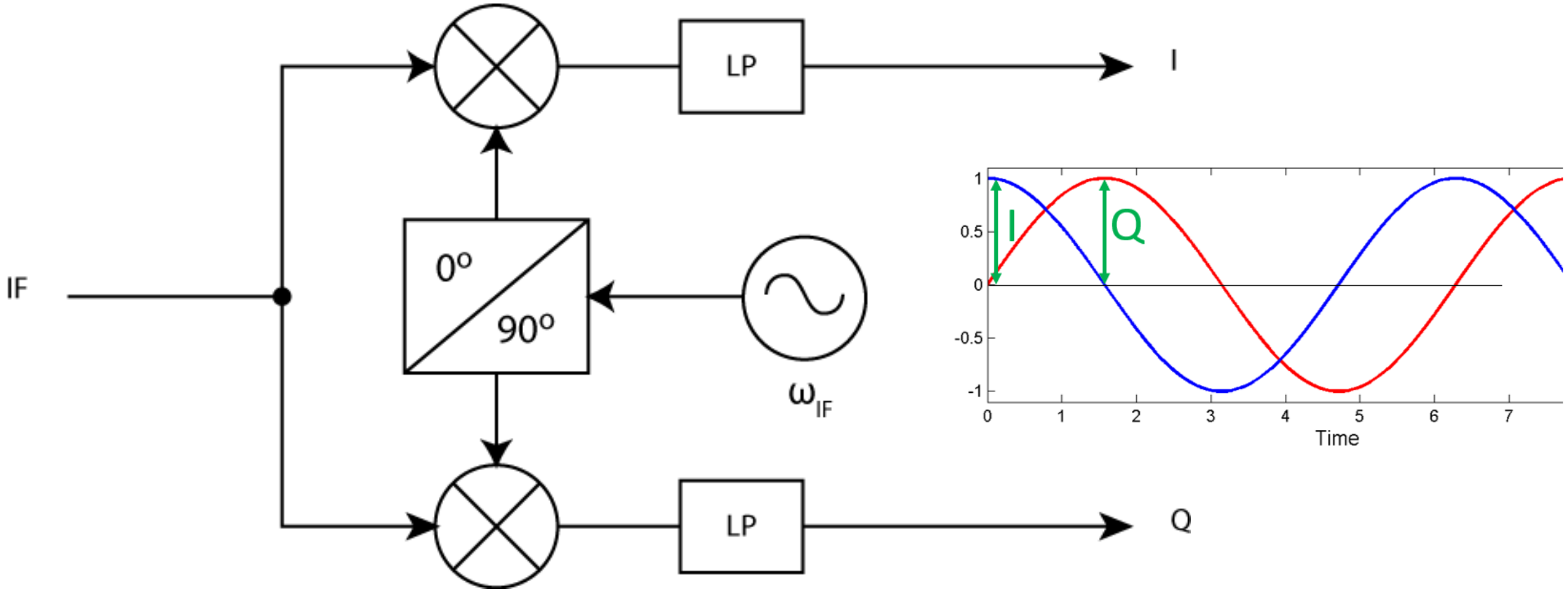


Don’t have time!

- Making my database
- Fetching samples from Sigwiki and others
- Matching collections
- All of that manually

But what if are lazy?

SDR and IQ

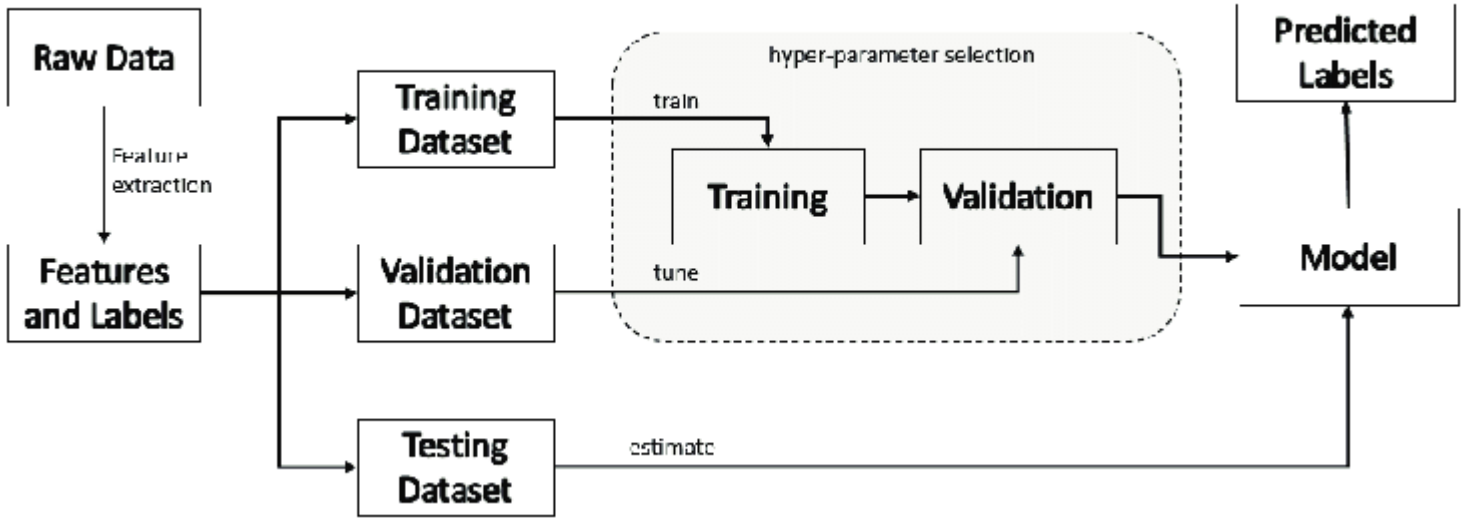


ML & DL

Me beginning in machine learning

Machine learning

- Science → learn from data
- Used to simplify complex rules applications: e.g. “spam filter”



Source: [A Machine Learning Approach to Road Surface Anomaly Assessment Using Smartphone Sensors]

Machine learning types

- Can be:
  - Supervised: feed the algo with desired solution → labels
    - Linear Regression
    - k-Nearest Neighbors
    - Logistic Regression
    - Super Vector Machines
    - Decision Trees and Random Forest
    - Neural Network

Machine learning types (2)

- Unsupervised:
  - Clustering (K-Means, DBSCAN, Hierarchical Cluster Analysis (HCA))
  - Anomaly detection and novelty detection (On-Class SVM, Isolation Forest)
  - Visualization (Kernel PCA, etc.)
  - Association rule learning (Apriori, Eclat)

Deep learning

- An application to Machine Learning
- Artificial neural network as a learning model
- Different kinds of layers

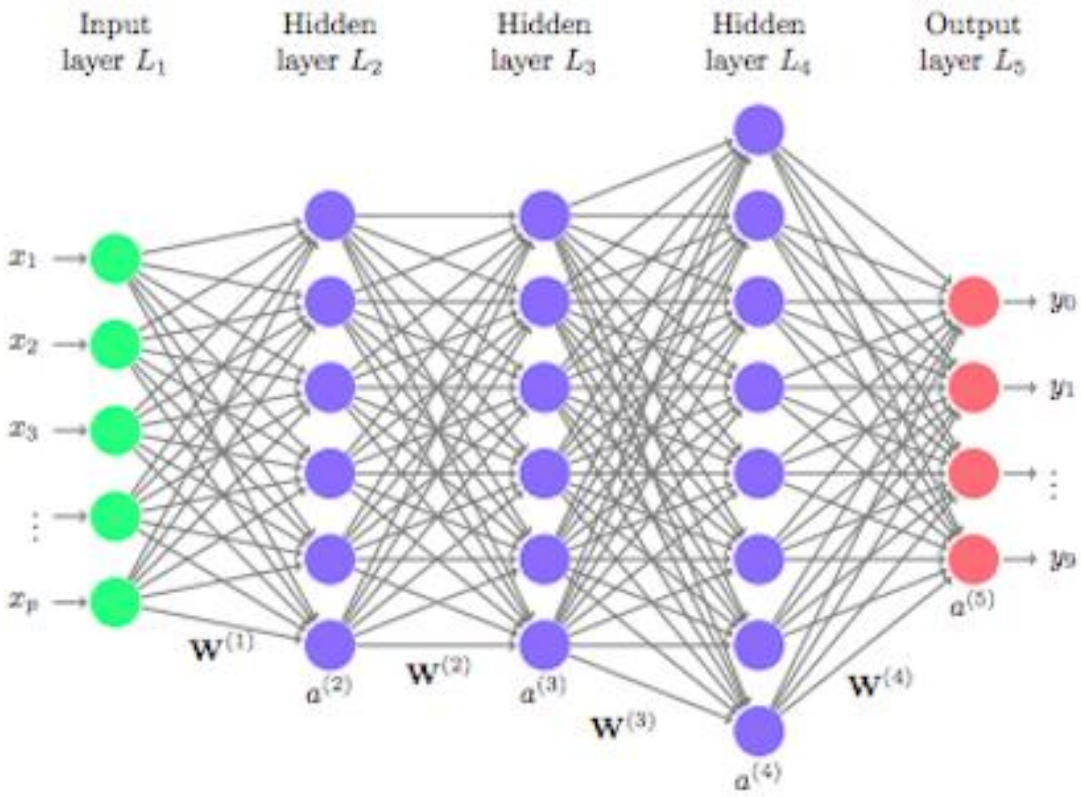


Image: UC Business Analytics R Programming Guide

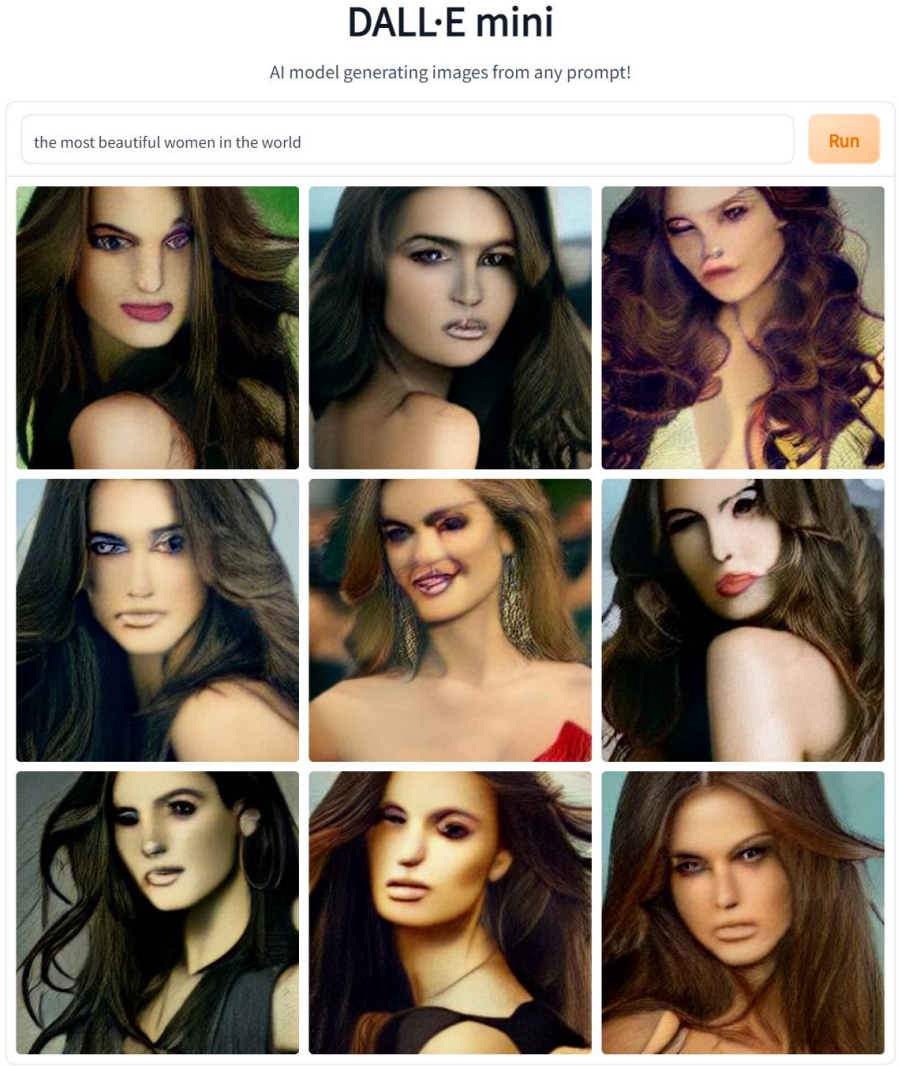
Good resources

- Hands-On Machine Learning with Scikit-Learn, Keras, and TensorFlow, 2nd Edition
- Coursera Machine learning and Deep Learning courses
- https://towardsdatascience.com/
- Etc.

Challenges

- Bad data
- Bad algorithm(s) in use
- Insufficient quantity of training data
- Noisy data
- Nonrepresentative set
- Overfitting
- Underfitting
- Etc.

A lot of chance to mess



This model is excellent!

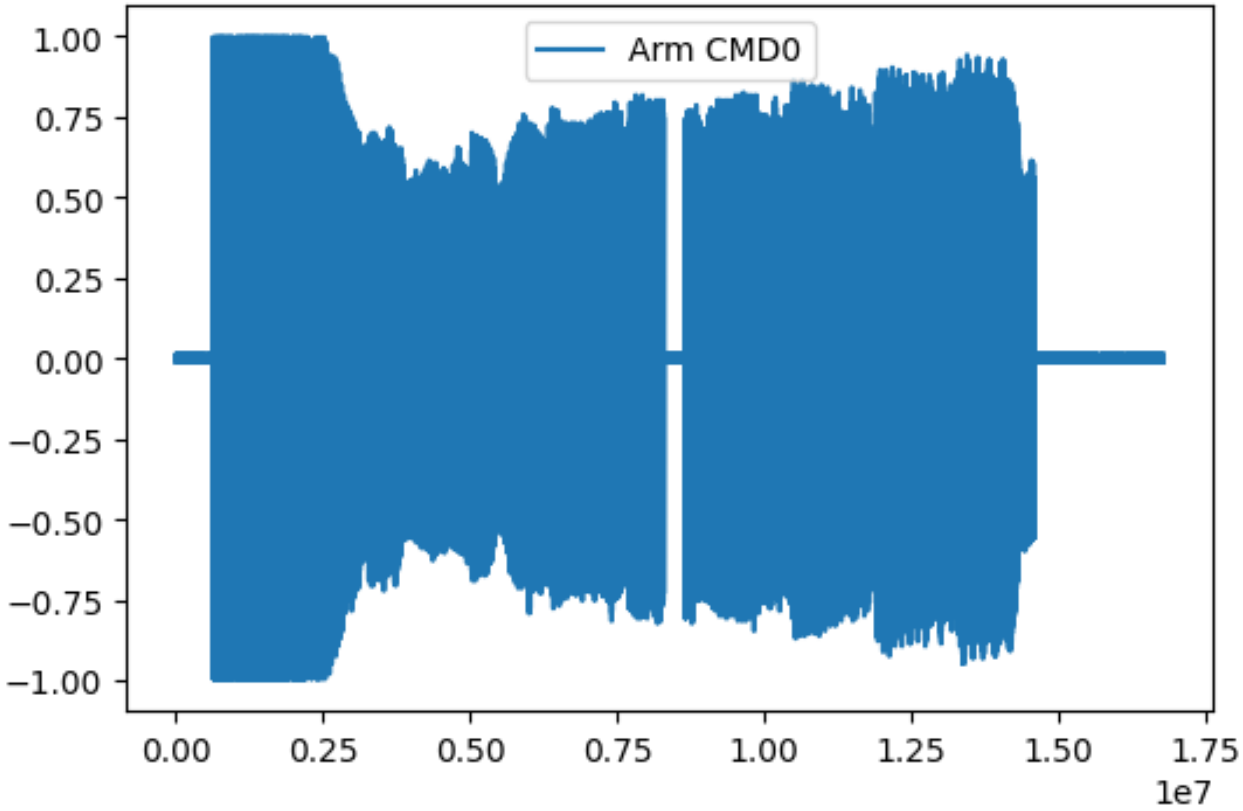
Model is as bad/good as your training set

- Need a lot of samples
- But filtered/clean samples
- Make a good balance between training and test sets
  - Warning! Test set always go at the end to test the model
  - Warning2: Careful with data and test splits
- Test different models → Ensemble learning is a win!

Machine learning for signal classification

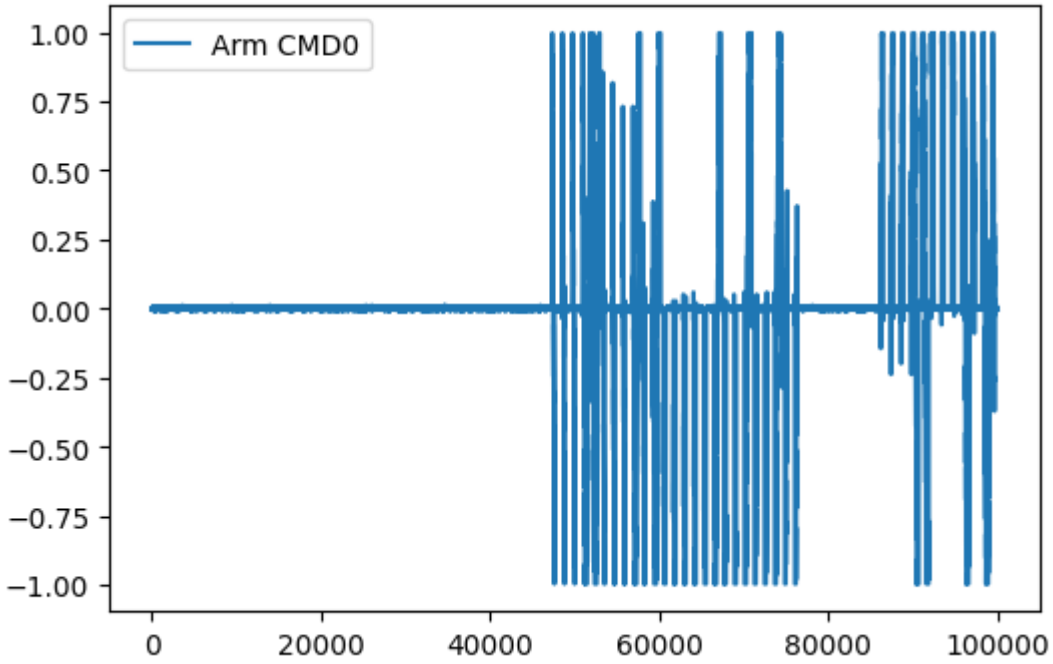
First capture we identified at an ISM frequency

- Doesn’t tell a lot
- Need to zoom in to see the properties
- There are maybe multiple packets



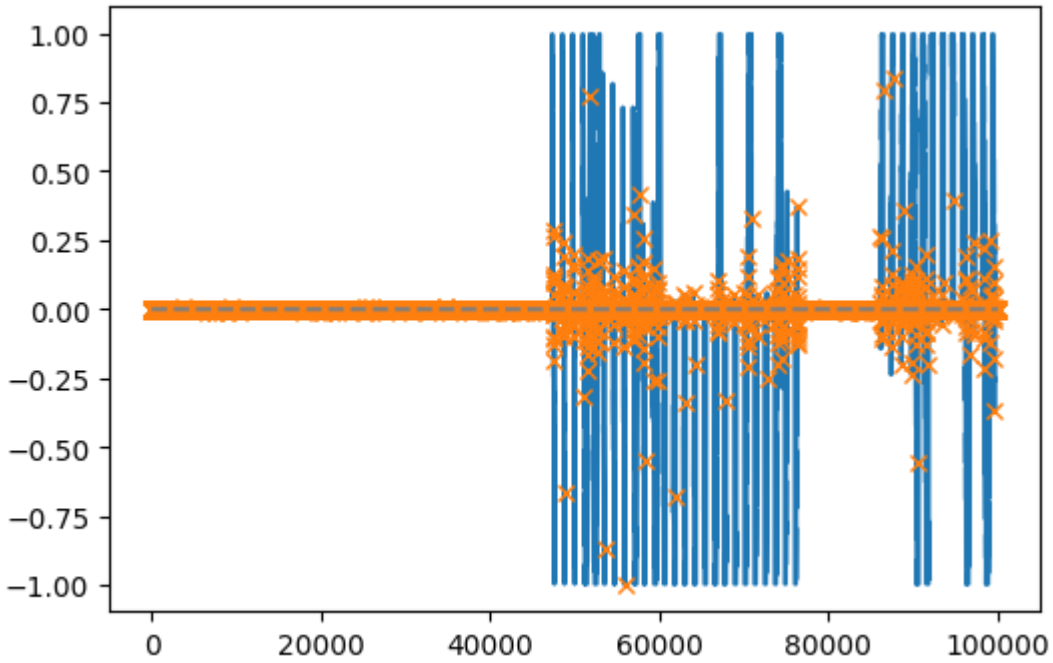
First capture zoomed

- Better → observe changes in amplitude → ASK/OOK
- Need to extract some properties (we can also apply some sound techniques):
  - Zero Crossing Rate
  - Mel-Frequency Cepstral Coefficients (even if applied to sound)
  - Roll-Off Point (even if applied to sound)
  - Number of peaks
  - Spectral Centroid
  - etc.

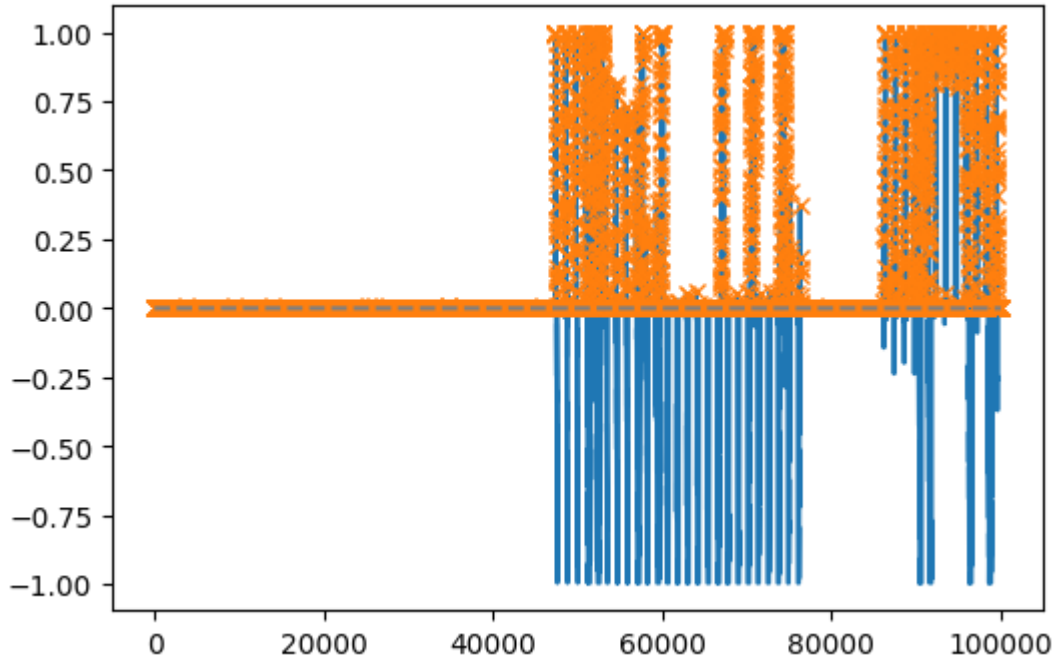


ZCR : Zero Crossing Rate

$$ZCR = \frac{1}{2N}\sum_{n=1}^{N} |sign(x[n]) - sign(x[n-1])|$$



Number of peeks

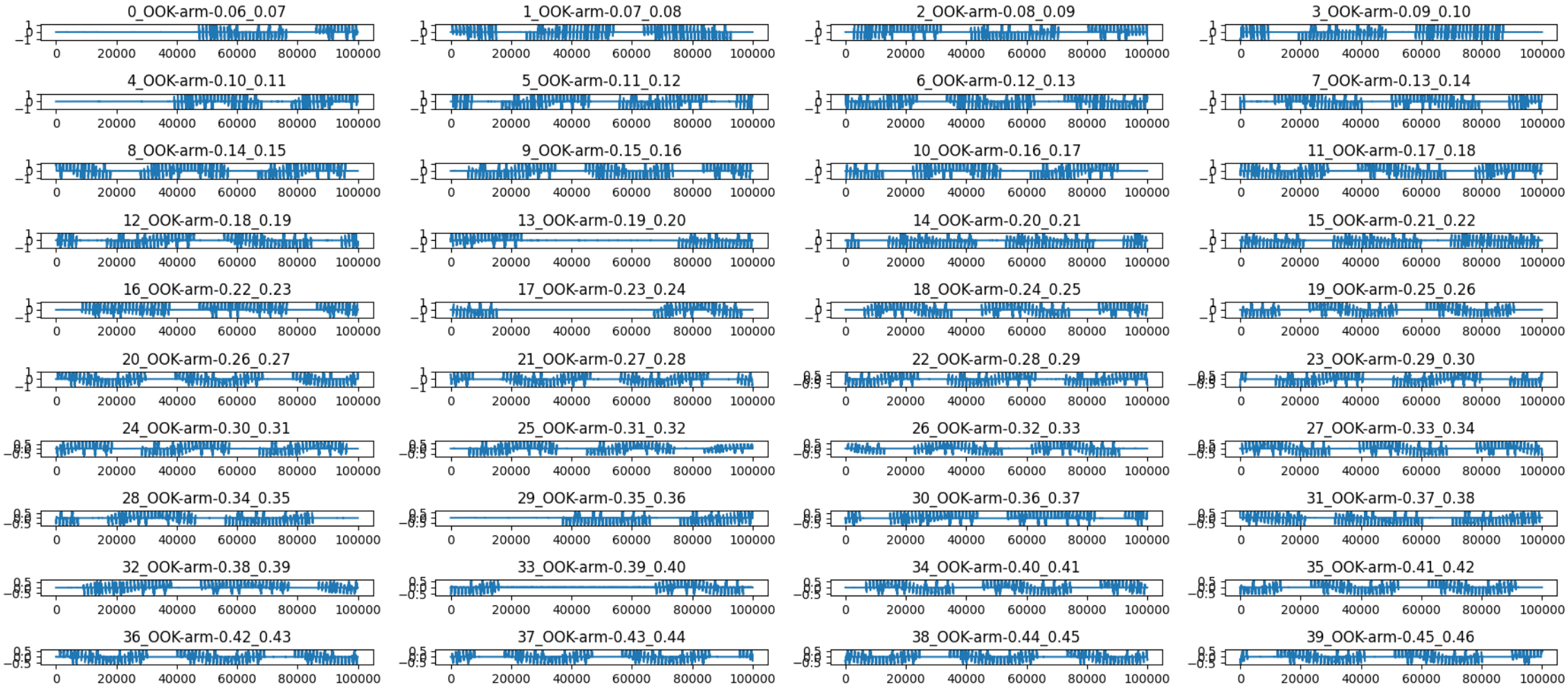


Our first list of features

```python
import pandas as pd

x = armbutton_01_slice.real

column_names = ['zcr', 'spectral_c', 'peaks' , 'label']
df = pd.DataFrame(columns = column_names)

def get_features(csignal, label):
    peaks, _ = find_peaks(csignal, height=0.99)
    return (len(np.where(np.diff(np.sign(csignal)))[0]), spectral_centroid(csignal), len(np.diff(peaks)), label)

df.loc[0] = get_features(x, "OOK")
df.head()
```

	zcr	spectral_c	peaks	label
0	35720	102043.176225	183	OOK

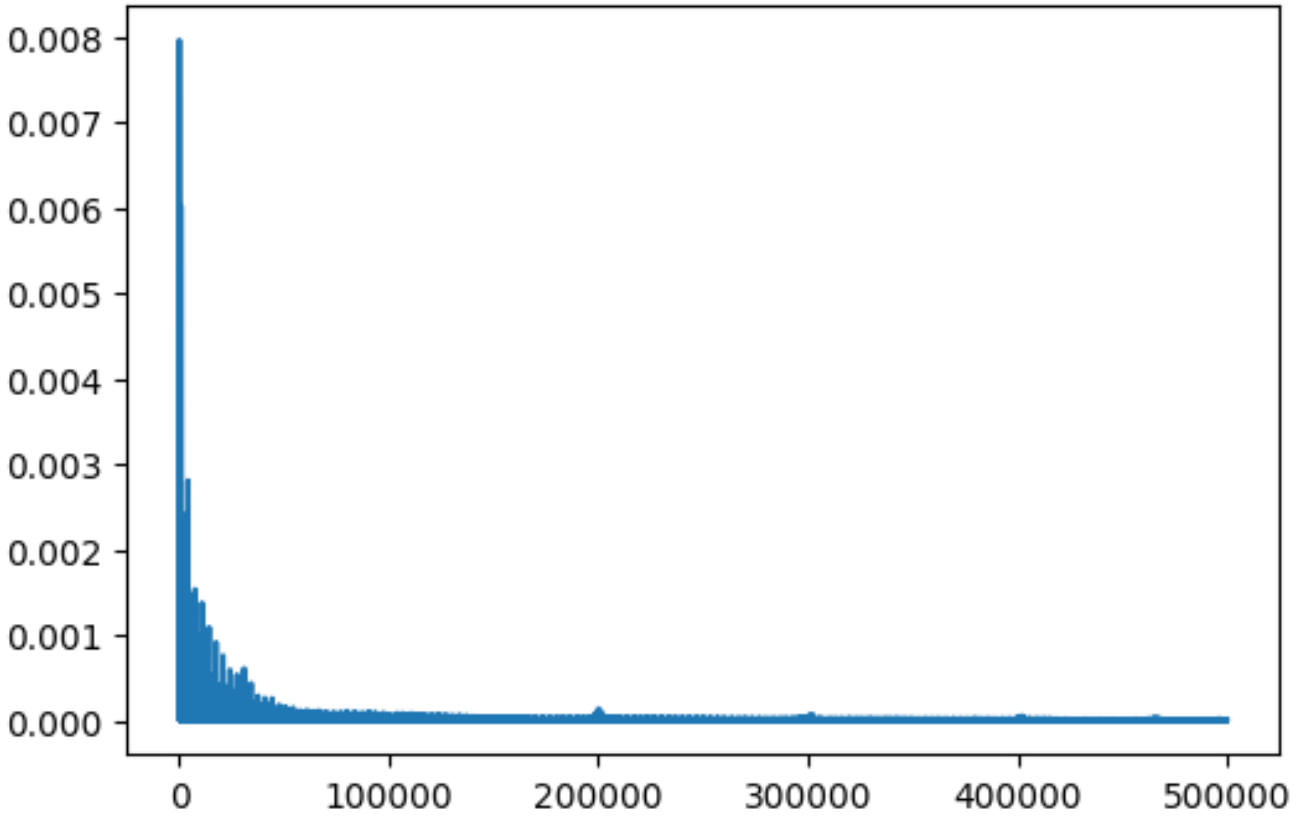
Making slices



All features for OOK

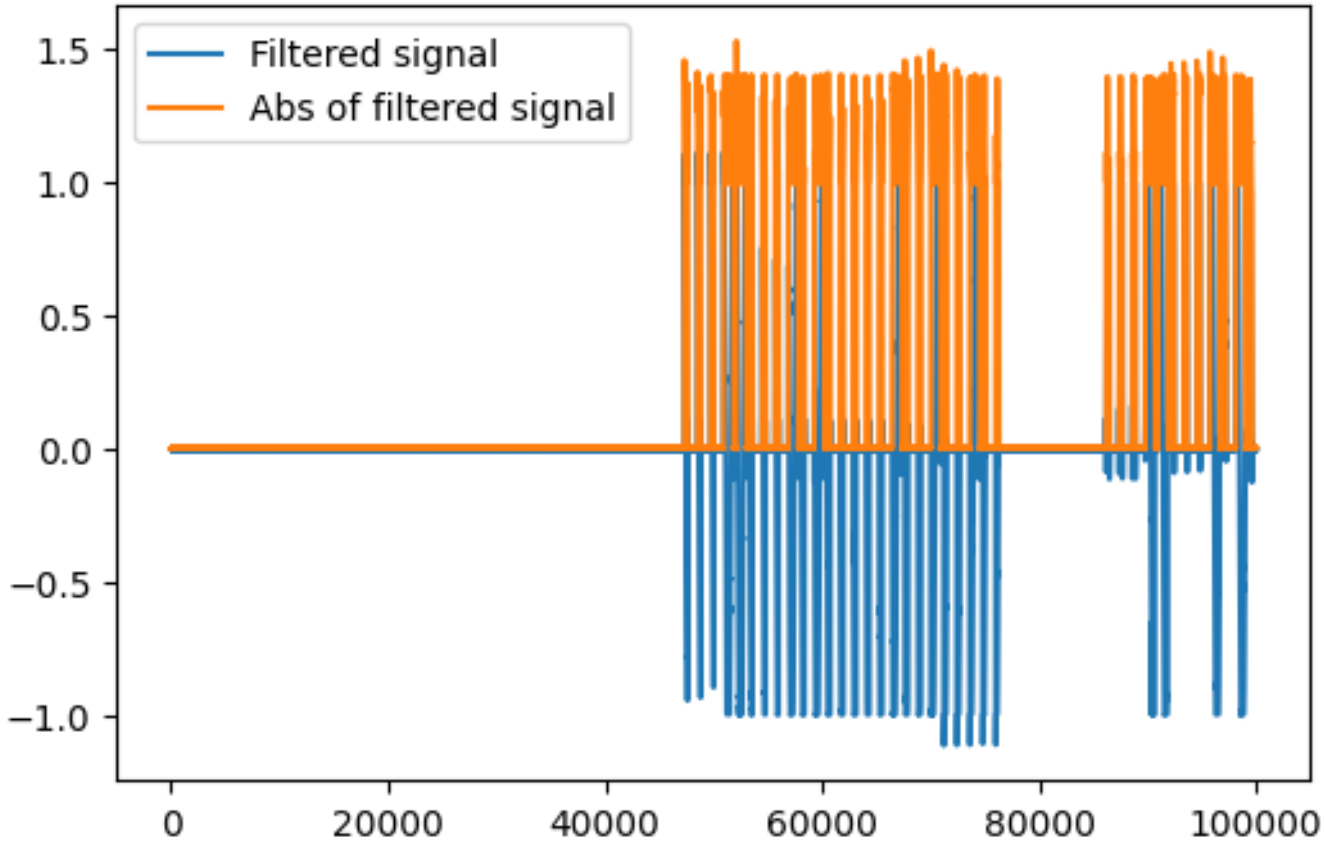
	zcr	spectral_c	peaks	label
0	35720	102043.176225	183	OOK
1	31570	112136.896603	286	OOK
2	30196	104925.260302	372	OOK
3	31894	107870.609573	303	OOK
4	35140	107022.365464	237	OOK
5	31257	106172.448807	328	OOK
6	29946	108299.517874	301	OOK
7	31224	106972.528967	328	OOK
8	30409	106918.584870	383	OOK
9	31027	104921.485225	328	OOK
10	31304	102660.881477	296	OOK
11	30050	104113.696990	333	OOK
12	31473	101537.998925	258	OOK
13	34870	103812.785526	248	OOK

FFT to reveal component



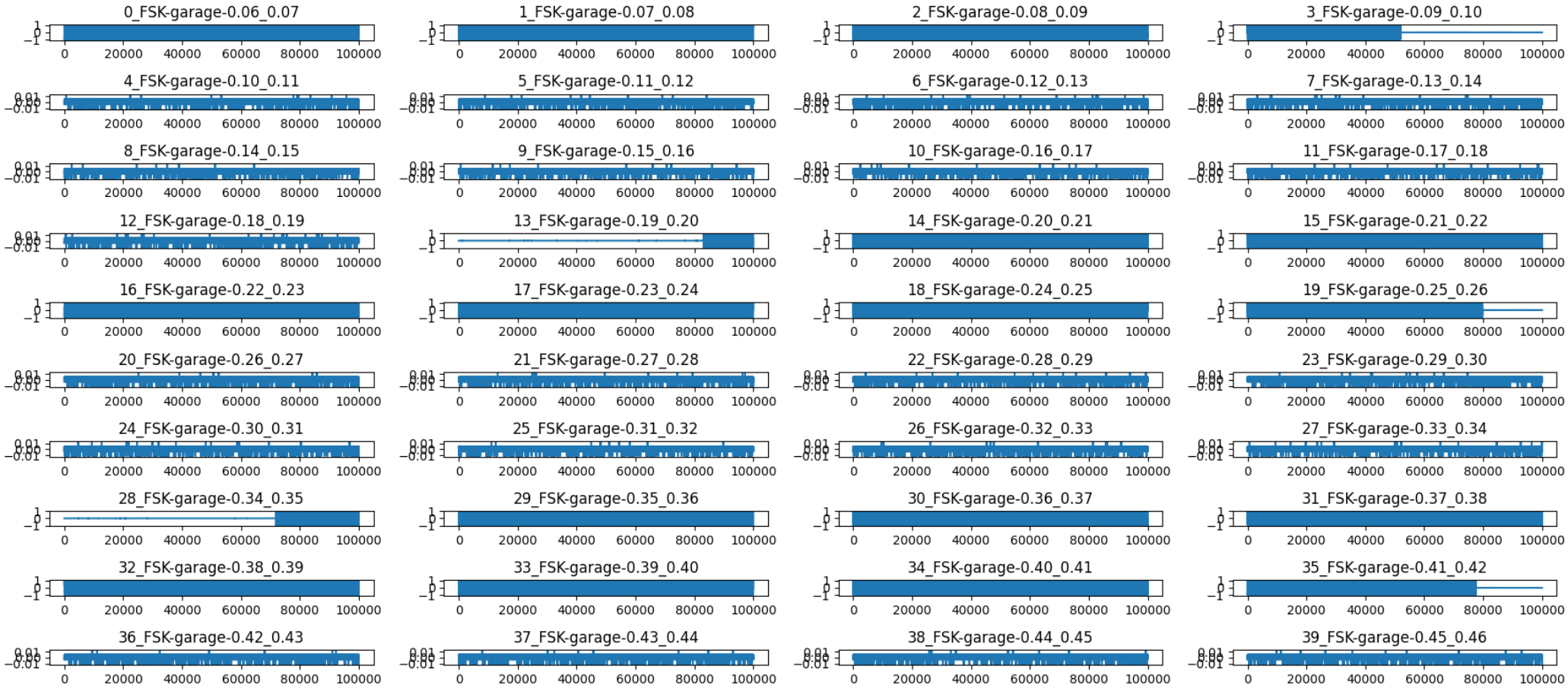
A simple low-pass filter would do the job !

Clean “packet” and it’s abs



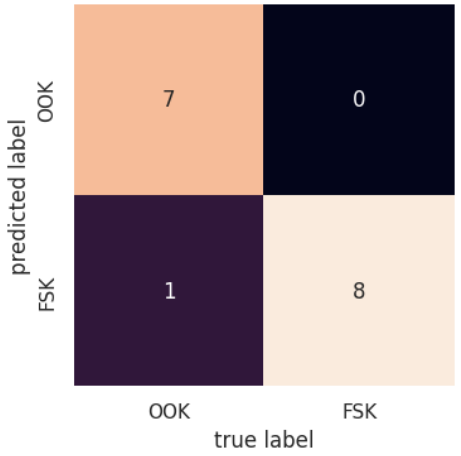
The signal can remain at default edge

Second capture : e.g. FSK



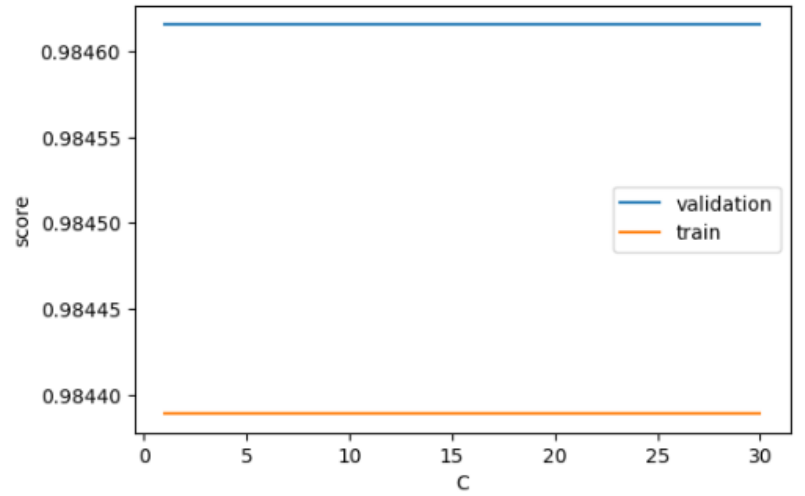
Use of SVM

- Results look great but can fail with more classes
- Need to test with != algorithms
- More data, of course
- But also, more features!




```
from sklearn.svm import SVC
from sklearn.model_selection import validation_curve
model_svm = SVC()
model_svm.fit(X_train, y_train)

print('Train score : ', model_svm.score(X_train,y_train))
print('Test score : ', model_svm.score(X_test,y_test))

k_3 = np.arange(1,31)
tr_score_3, val_score_3 = validation_curve(model_svm, X_train, y_train, param_name='C', param_range=k_3, cv = 5)

#5 splits sets de cross validation, on fait la moyenne des scores obtenus sur chacun des 5 splits

train = model_svm.predict(X_train)
predictions = model_svm.predict(X_test)

plt.plot(k_3, val_score_3.mean(axis = 1), label = 'validation')
plt.plot(k_3, tr_score_3.mean(axis = 1), label = 'train')

plt.ylabel('score')
plt.xlabel('C')
plt.legend()
```

```
Train score :  0.984375
Test score :  0.9375
<matplotlib.legend.Legend at 0x7f8ac3f7a390>
```



Random forest

- Found a got hyperparameters

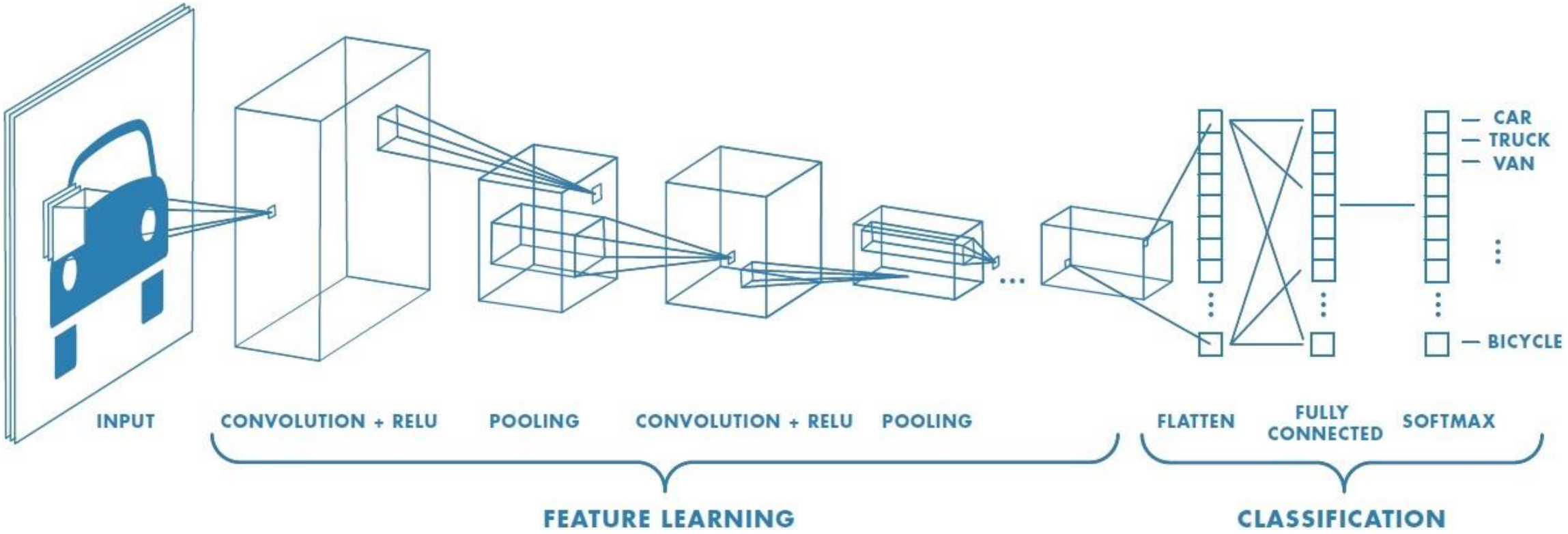
```
Fitting 3 folds for each of 4 candidates, totalling 12 fits
```

	max_depth	min_samples_split	n_estimators	Accuracy
0	20.0	2	500	0.966667
1	20.0	2	4000	0.966667
2	NaN	2	500	0.966667
3	NaN	2	4000	0.966667

- But accuracy to good to be true for large sets

CNN implementation

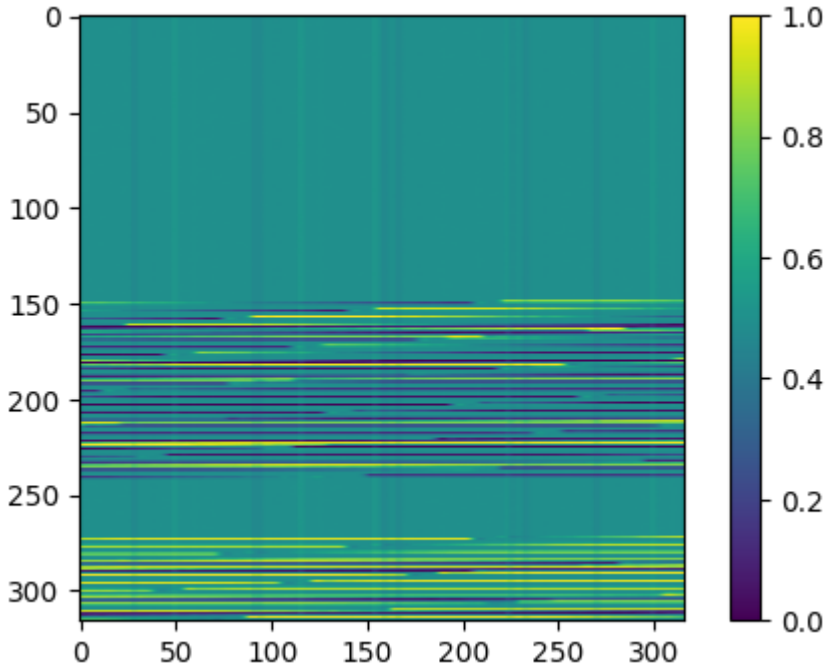
Convolutional Neural Network



Source: https://medium.com/@RaghavPrabhu/understanding-of-convolutional-neural-network-cnn-deep-learning-99760835f148

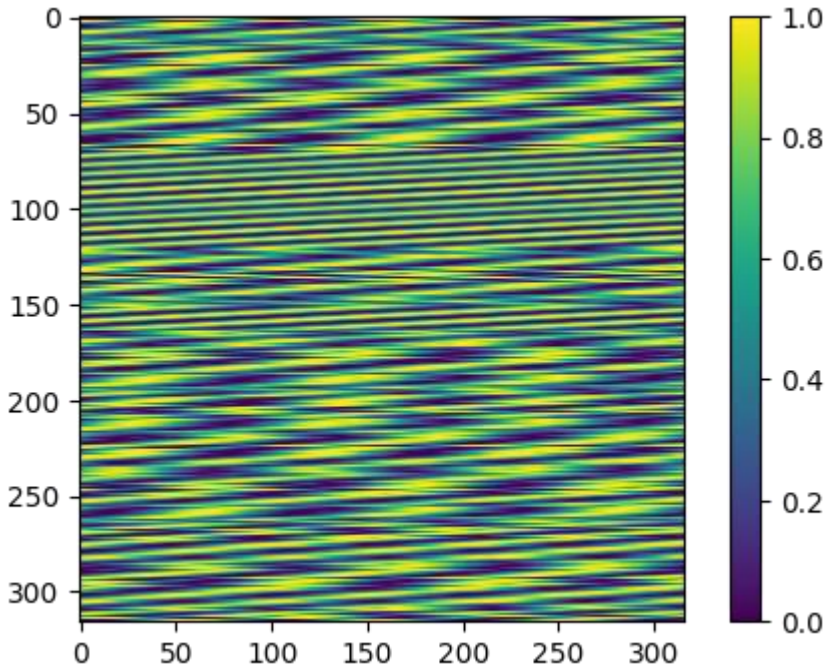
Convolutional Neural Network (2)

- We can miss a lot of features when extracting them from a signal on our own
- It’s possible to transform the signal to image for the OOK signal:



FSK to image

- We can notice a difference in the pattern:

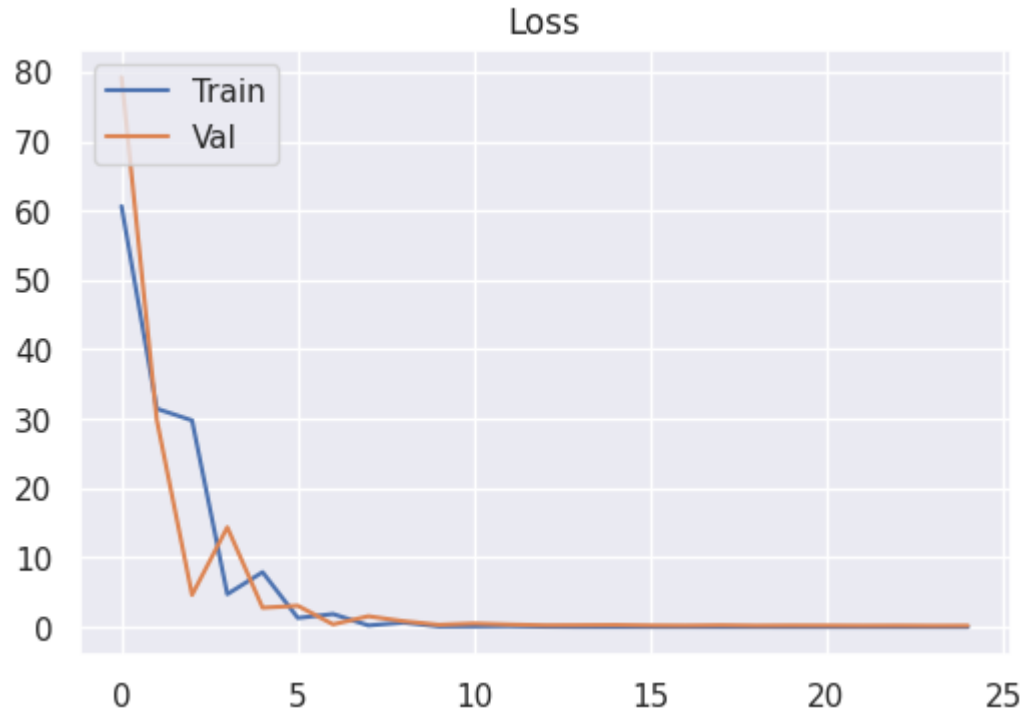


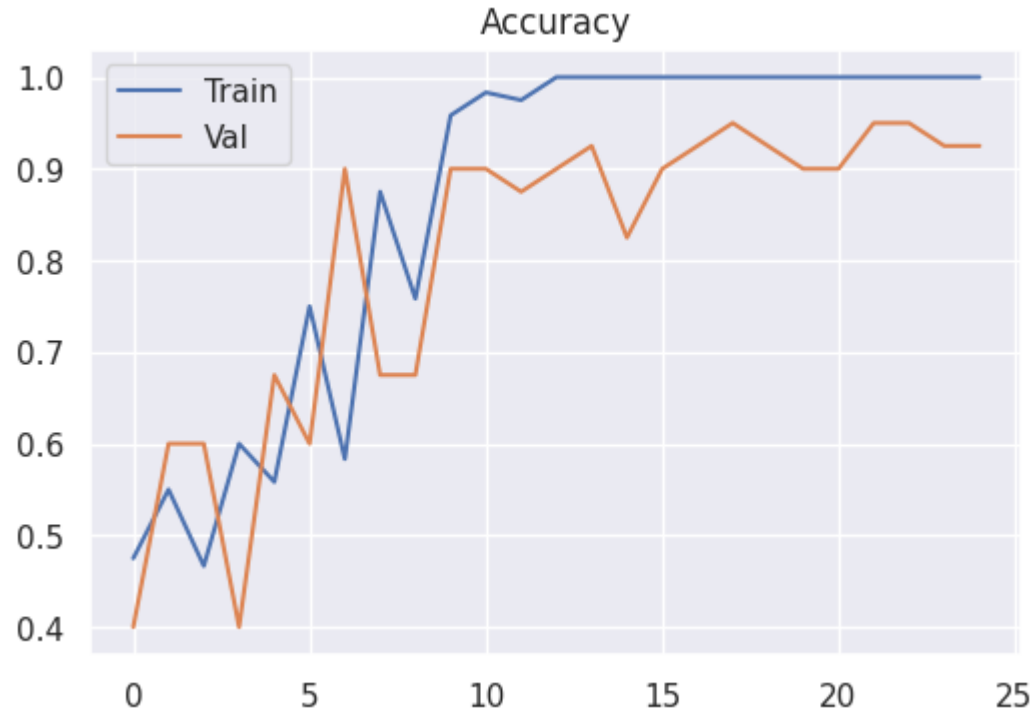
Results

- With 80 samples each
- 25 Epochs
- Following model:

```
Model: "sequential"
_________________________________________________________________
 Layer (type)                Output Shape              Param #
=================================================================
 conv2d_1 (Conv2D)           (None, 314, 314, 64)      640

 max_pooling2d_1 (MaxPooling  (None, 157, 157, 64)     0
 2D)

 flatten_1 (Flatten)         (None, 1577536)           0

 dropout_1 (Dropout)         (None, 1577536)           0

 dense_1 (Dense)             (None, 64)                100962368

 dense_2 (Dense)             (None, 2)                 130

=================================================================
```

Results (2)


Loss
Train
Val
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25


Accuracy
Train
Val
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
5
10
15
20
25

Details in the Jupyter notebook

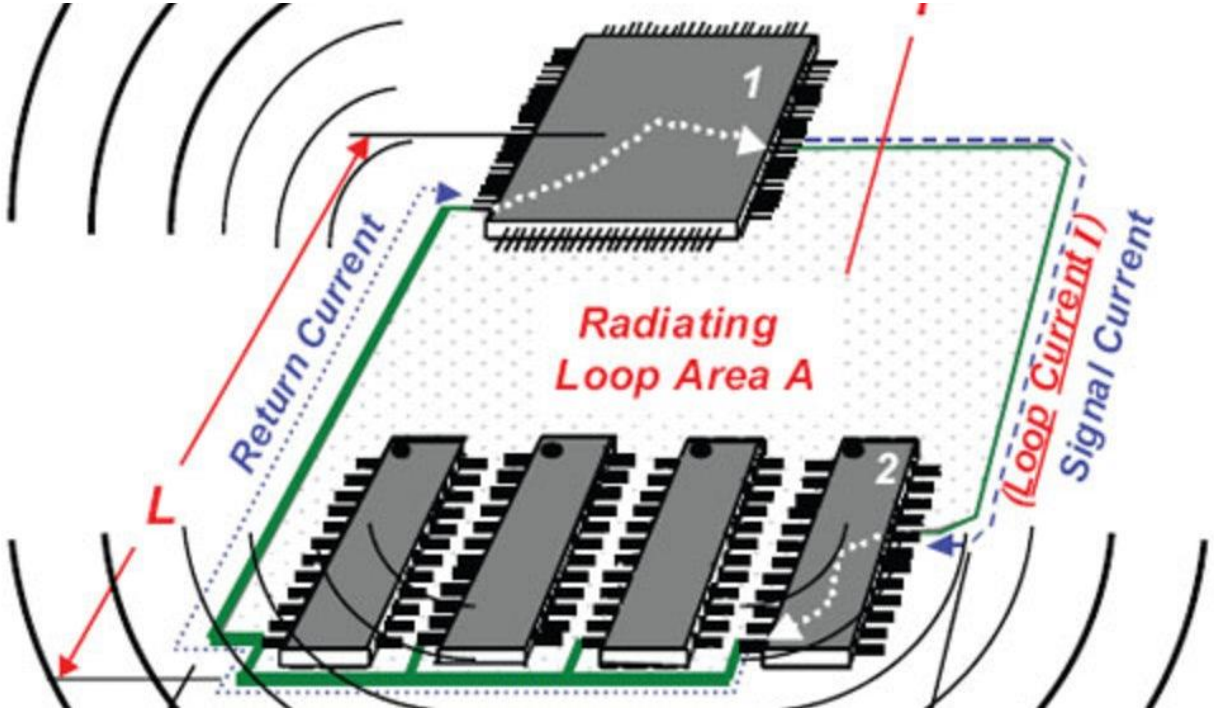
Other applications: EM attacks

EM side channels

- Compromise electromagnetic emanations → radiative coupling
- We try to infer what was computed
- Like power side channels → HW emits EM radiation → computation
  - Amplitude → proportional to consumed power
  - Some computations require +/- power
    - In CMOS → power is related to data being processed
- EM radiation → leaks certain operations:
  - Operation of encryption
  - PIN/key pressed
  - Memory RW

Differential-mode radiation

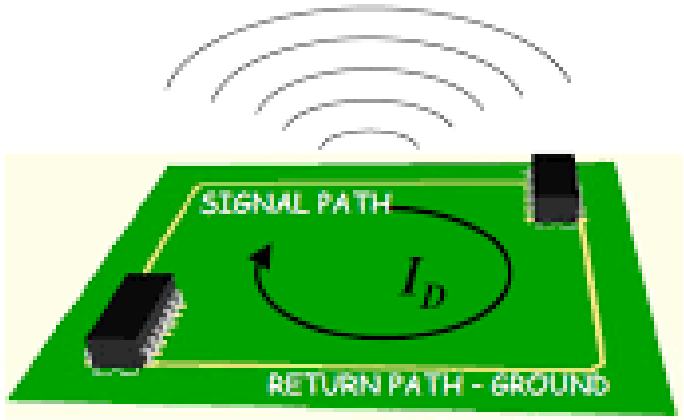
- Loops formed by components (circuit traces, ribbon cables, etc.)
- Act like an antenna → radiate
- Can be avoided with some shielding



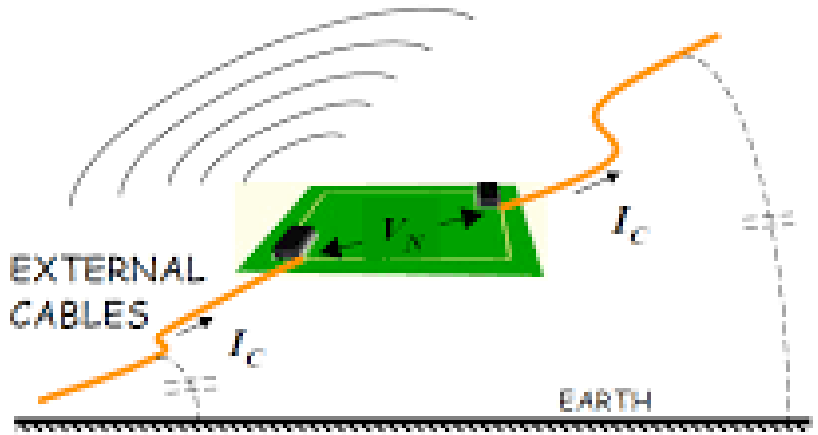
Source : electronicdesign.com

Common-mode radiation

- Undesired internal voltage drops in the circuit
  - Generally, in the ground loop
- External cable act as an antenna
- Difficult to control and control



DIFFERENTIAL MODE RADIATION

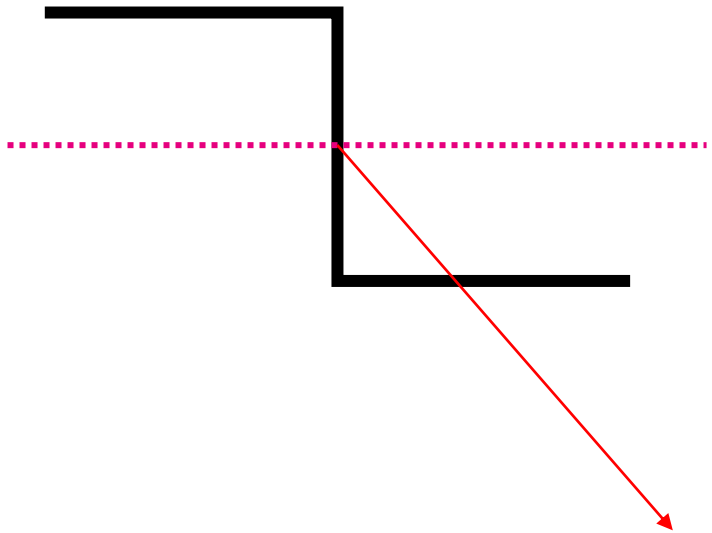


COMMON MODE RADIATION

Source : ursi.org

Direct emanations

- Provided straight by the wire transmitting sensitive data
- Faster is the transition → intense radiation



The activity of D Flip Flop (DFF) → commuting at HF ~1ns

EM wave emitted at max frequency → duration rise/fall time

Unintentional/Indirect Emanations

- Components are at short distance from each other
- Interaction with active electronic components → induce new type of radiations
  - Modulations, and inter-modulations (frequency, phase, and amplitude)
  - And carrier signal (clock and its harmonics)
- Can be observed at greater distance than direct emanations → observing harmonics in different distances
- Which frequency?
  - Use of periodic activity T in second, $f = 1/T$
  - Other harmonics → *2f, 3f, 4f*, etc.
  - Can be modulated often in AM with another operating clock “fc” → fc ± f, fc ± 2f, etc.

Side-channels applications

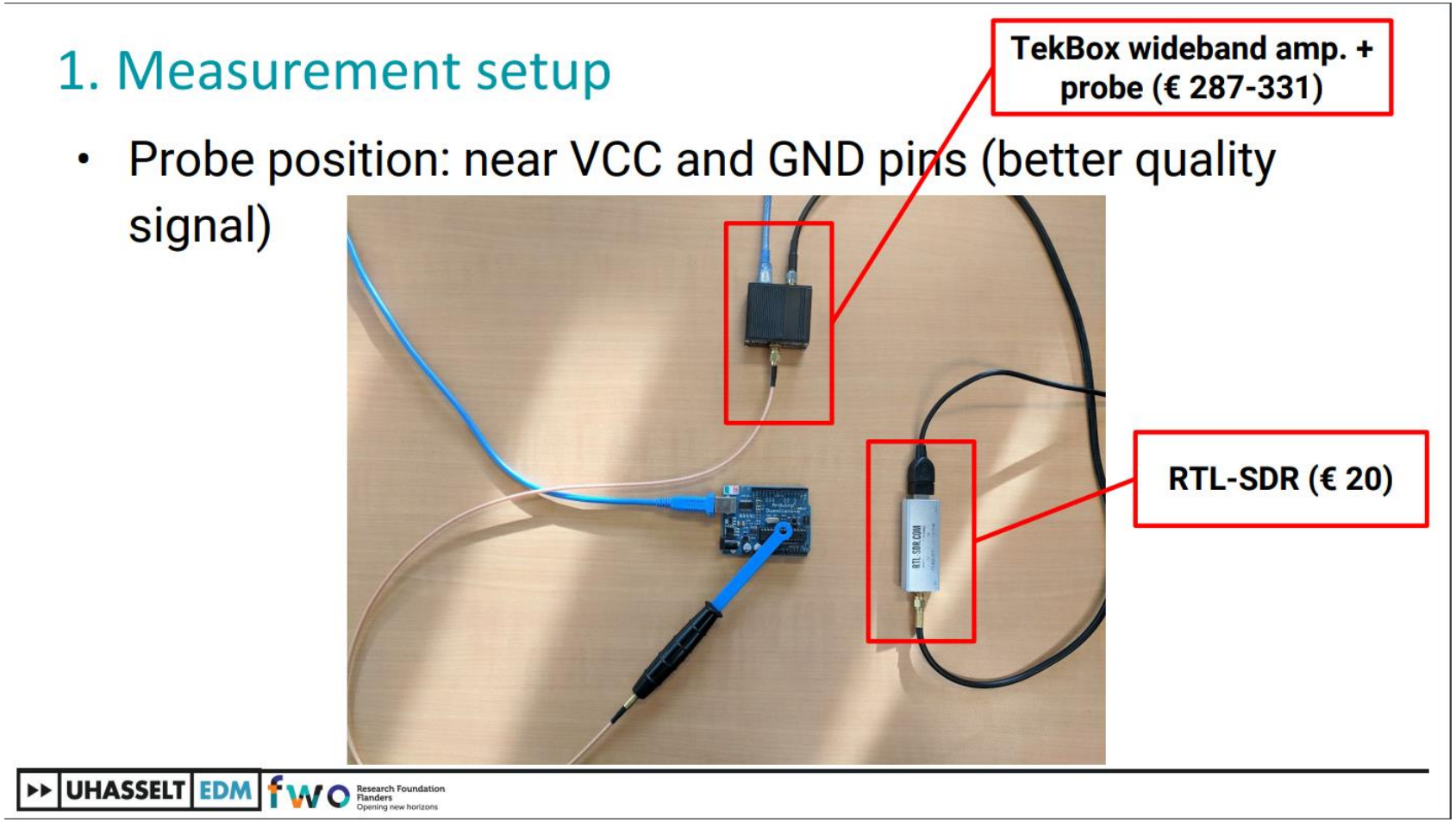
Side-channel attack on Ledger blue

By Thomas Roth, Josh Datko, Dmitry Nedospasov

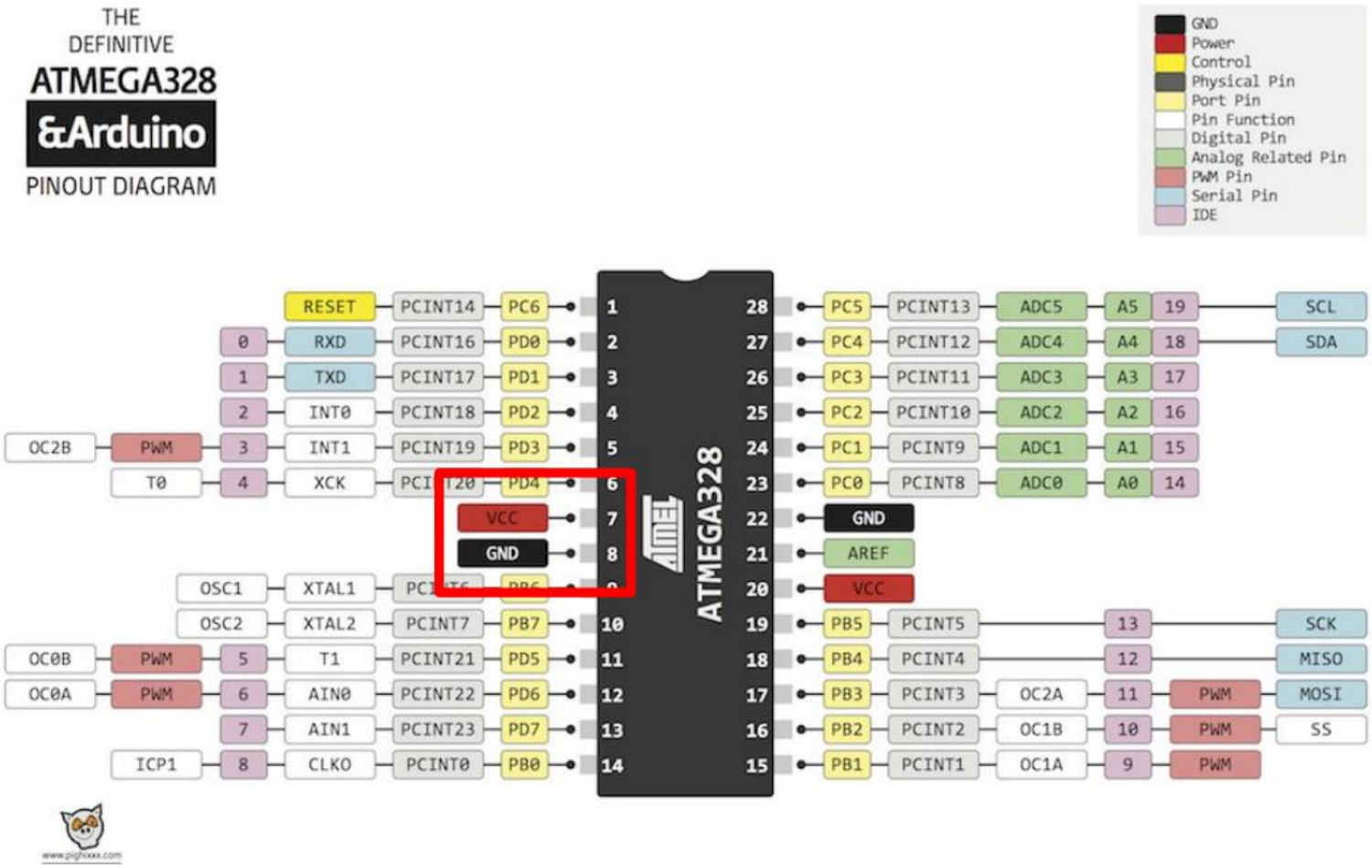
Leaking secrets of a device

AES CEMA attack on Arduino Duemilanove

- Performing Low-cost Electromagnetic Side-channel Attacks using RTL-SDR and Neural Networks by Pieter Robyns



Pins to target for better signal



Leakage Models

- Two common models:
  - Hamming Weight Model → linear relation between the number of bits “1” and power

$$HW(D) = \sum_{j=0}^{n-1} d_j$$ (D: input data, j bit, n: number of bits)

  - Hamming Distance Model → make use of dynamic leakage

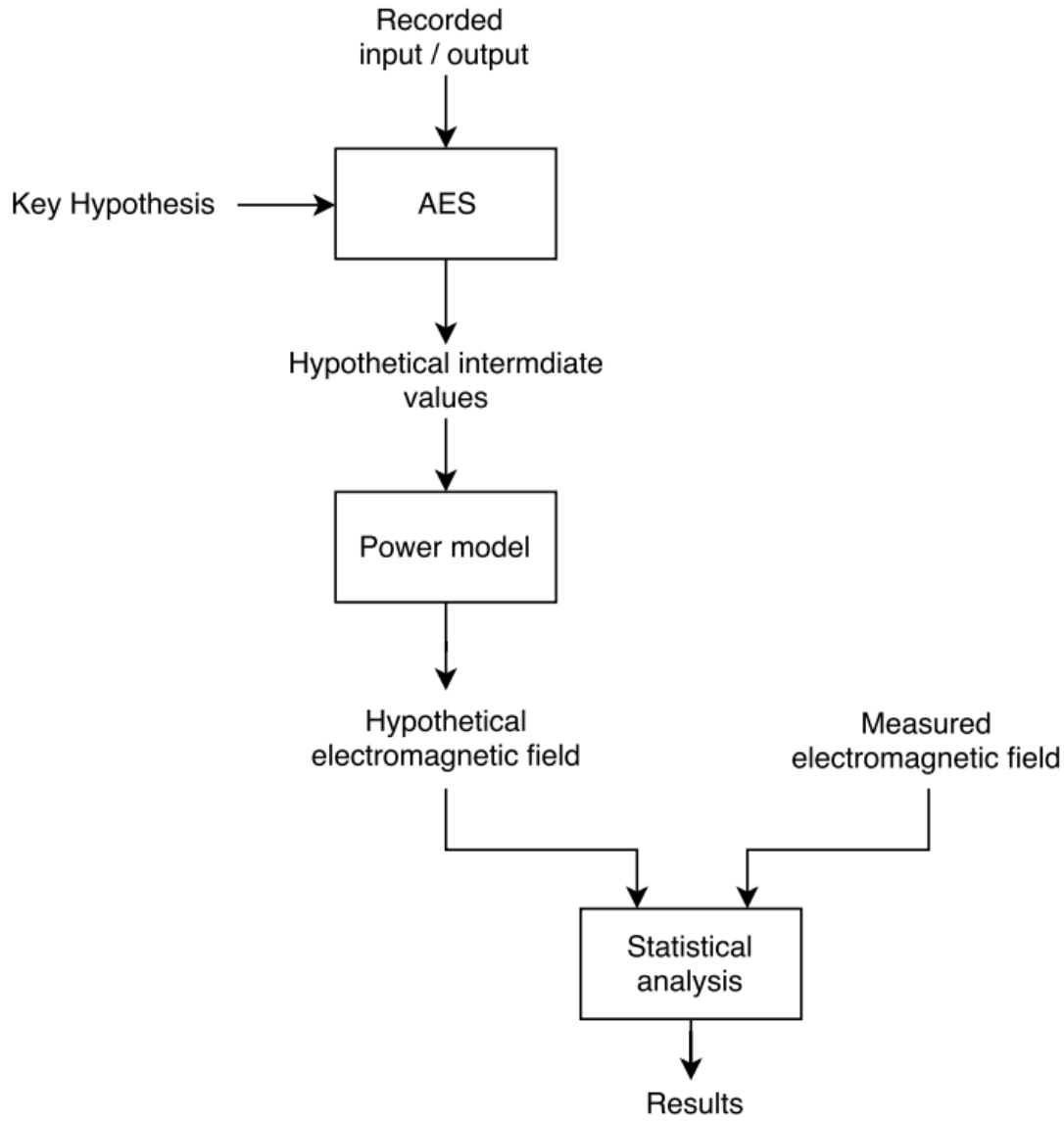
$$HD(D, D') = HW(D \oplus D')$$

(D and D’ → two input bytes/words)

Side-channel Attacks

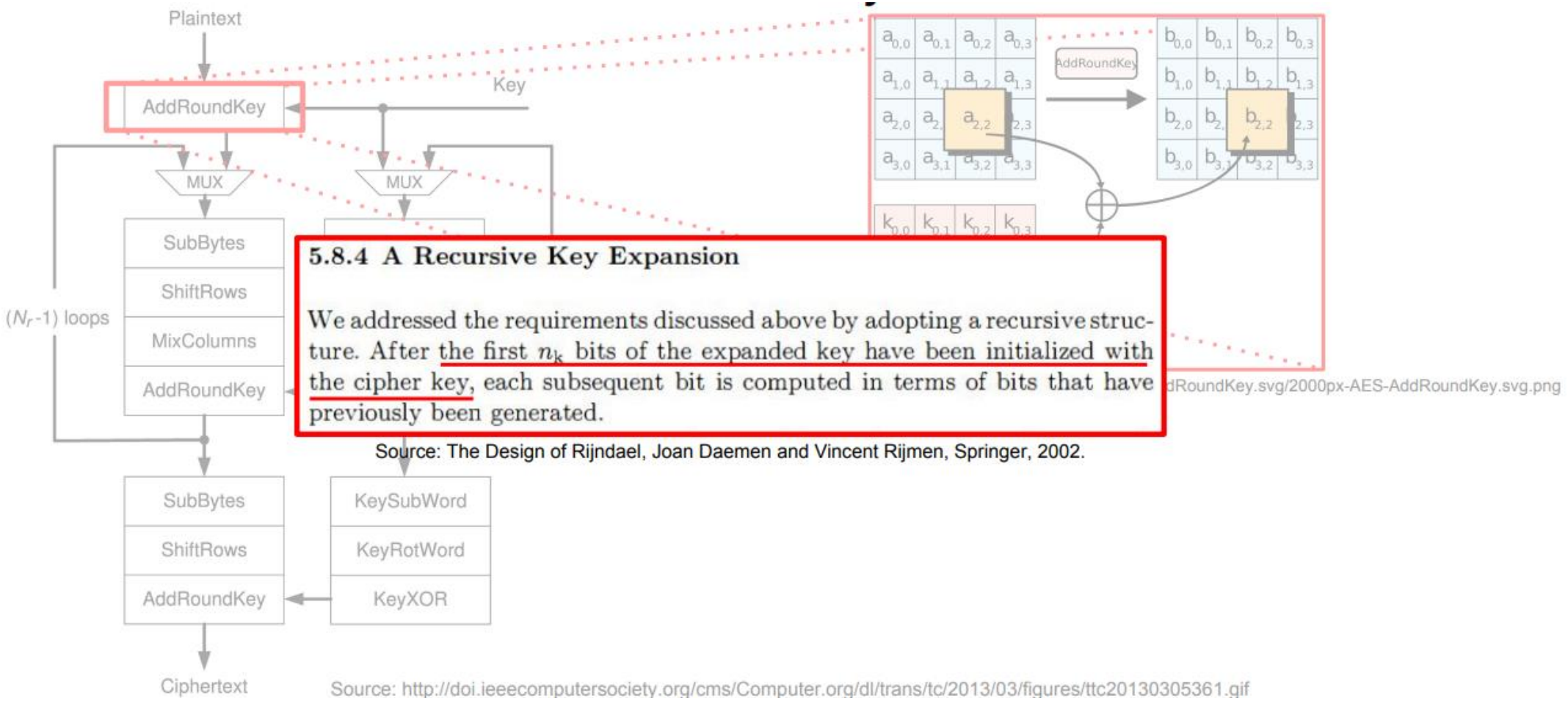
- Main attacks:
  - SEMA: Simple Electromagnetic Analysis → comes from SPA (visual for RSA e.g., and template)
    - Template is often used in AES → high frequency and noise
    - But need a similar device to characterize them and search space grow a lot when doing modeling leakage
  - DEMA & CEMA : Differential and Correlation Electromagnetic Analysis
  - TVLA: Test Vector Assessment → consisting of 1800 Welch's t-tests [18] knowing the plaintexts and the secret key.

DEMA & CEMA



Source: Far-field Correlation Electromagnetic Analysis attacks against AES in real-world applications F. van Tienen

CEMA attack on AES



5.8.4 A Recursive Key Expansion

We addressed the requirements discussed above by adopting a recursive structure. After the first n_k bits of the expanded key have been initialized with the cipher key, each subsequent bit is computed in terms of bits that have previously been generated.

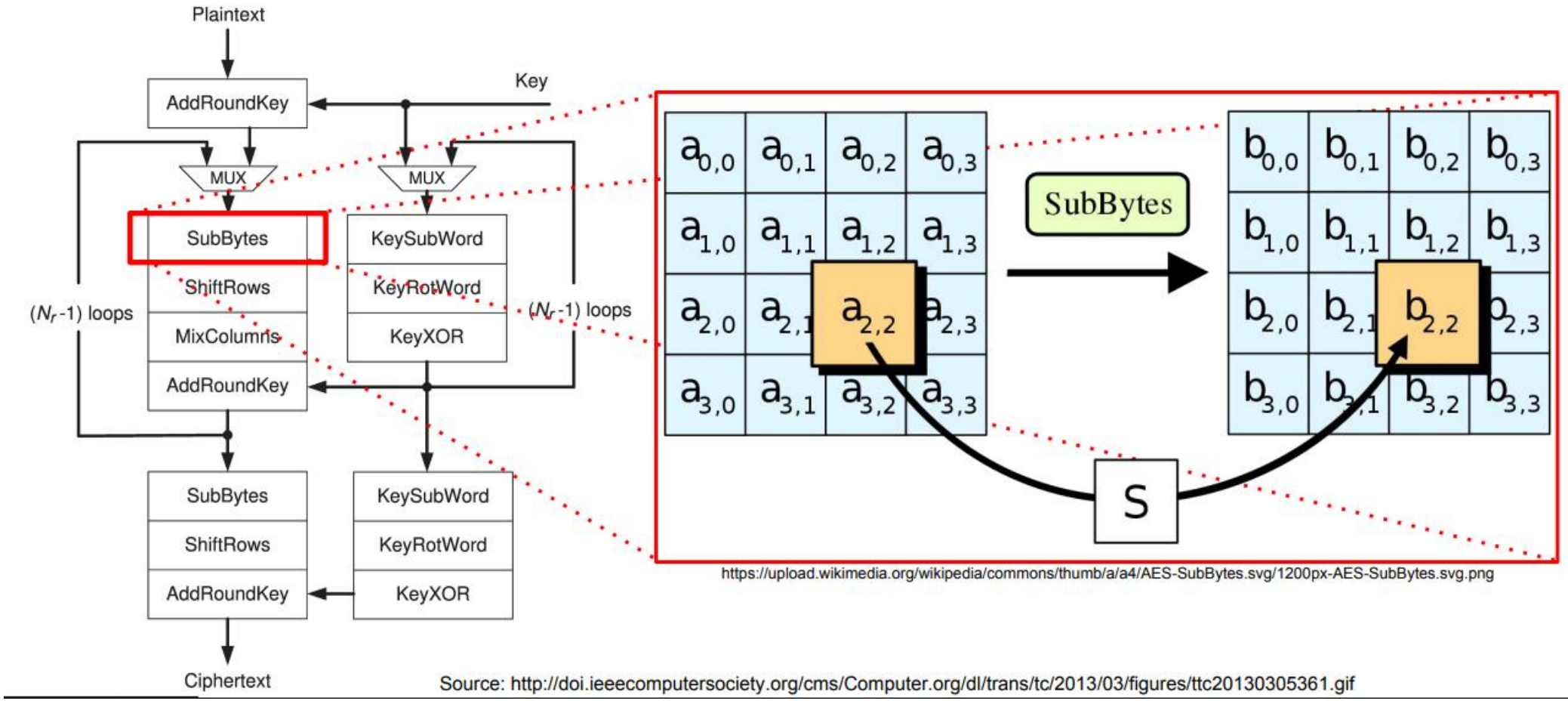
Source: The Design of Rijndael, Joan Daemen and Vincent Rijmen, Springer, 2002.

dRoundKey.svg/2000px-AES-AddRoundKey.svg.png

Source: http://doi.ieeecomputersociety.org/cms/Computer.org/dl/trans/tc/2013/03/figures/ttc20130305361.gif

Source: https://archive.fosdem.org/2019/schedule/event/sdr_em_sidechannel_attacks/attachments/slides/2931/export/events/attachments/sdr_em_sidechannel_attacks/slides/2931/robyns2019fosdem.pdf

CEMA attack on AES (2)



Source: http://doi.ieeecomputersociety.org/cms/Computer.org/dl/trans/tc/2013/03/figures/ttc20130305361.gif

Source:
https://archive.fosdem.org/2019/schedule/event/sdr_em_sidechannel_attacks/attachments/slides/2931/export/events/attachments/sdr_em_sidechannel_attacks/slides/2931/robyns2019fosdem.pdf

EMMA framework

- Let’s see: https://github.com/rpp0/emma

Conclusion

Lazy people gonna hate

- There is a magical algorithm for all datasets and purposes
  - Still a lot of work
  - Improve things within an Ensemble
  - It’s good also to generate clean signals! → less noise to learn + more samples
- But we can also take some inspiration from some great work:
  - Enhanced Low SNR Radio Signal Classification using Deep Learning, AI Wireless 2020 in National Chiao Tung University
  - And other → lot of GitHub projects

Thank You

Please contact us:

contact@penthertz.com

+33 1 73 13 82 79

penthertz.com