IEEE S&P 2022

Noise-SDR: Arbitrary Modulation of Electromagnetic Noise from Unprivileged Software and Its Impact on Emission Security

https://github.com/eurecom-s3/noise-sdr

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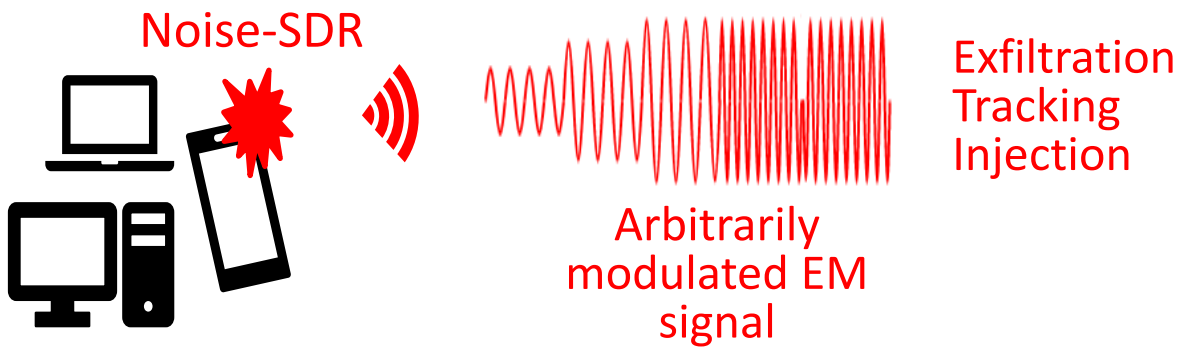

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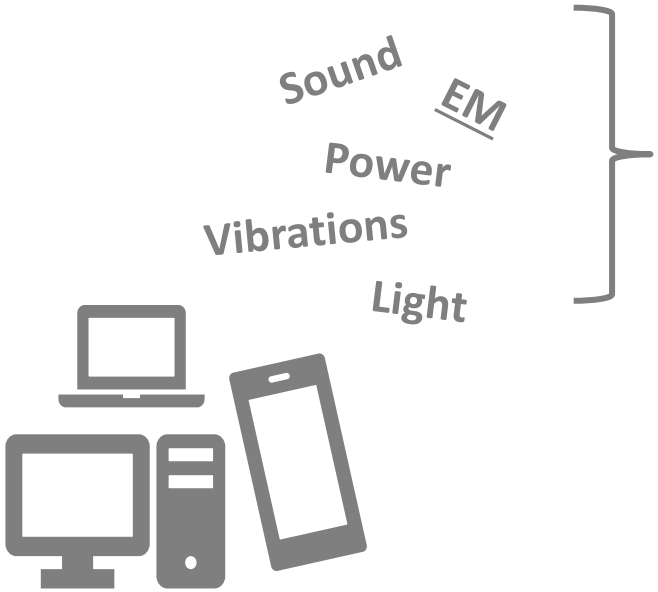
Context: Emission Security



Compromising emanations
Related to digital activity

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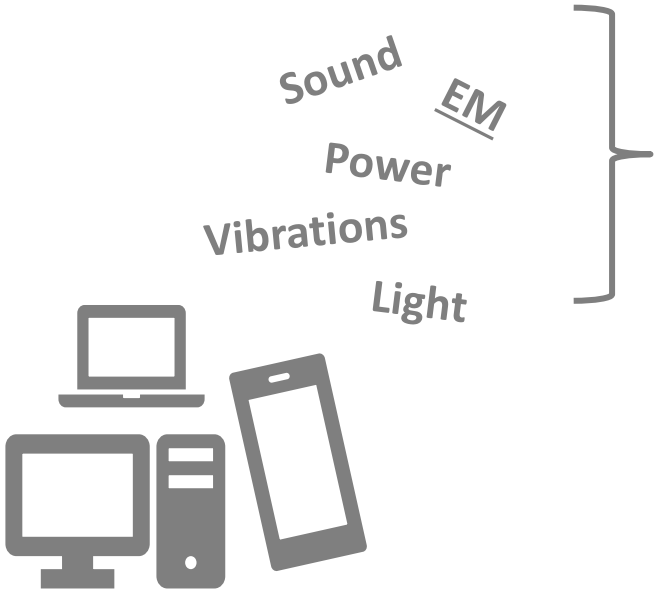

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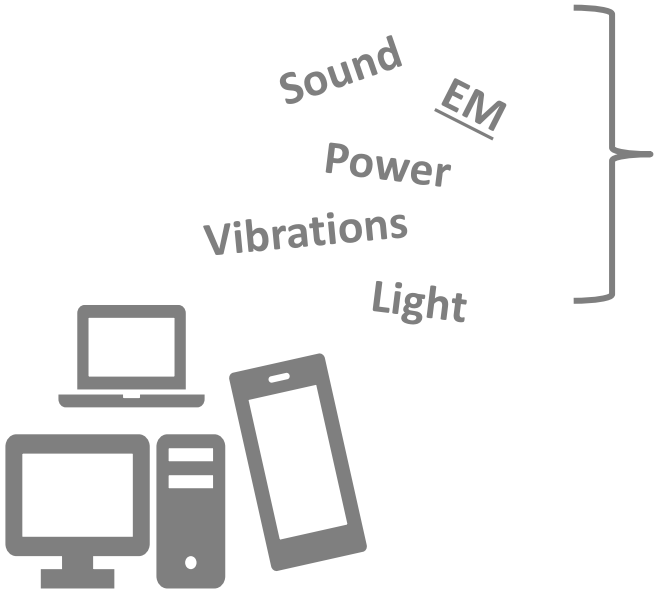

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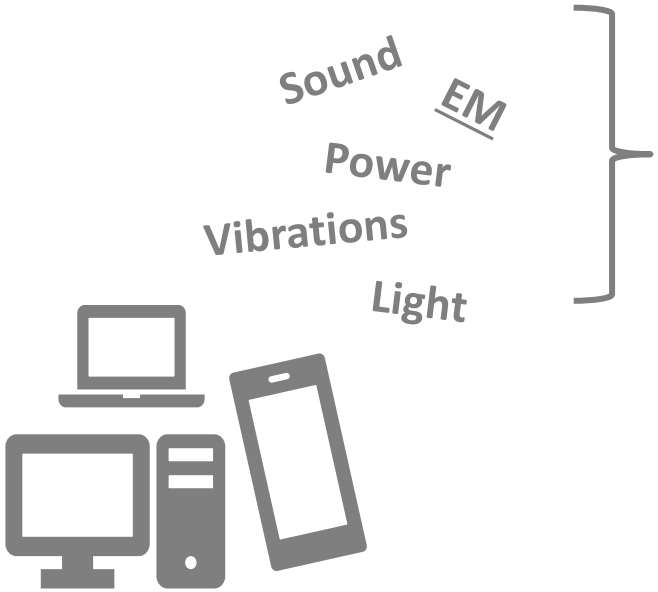

Compromising emanations
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- **Key => Side Channel**
- **Plaintext => TEMPEST**
- **Covert Channel => Soft-TEMPEST (active modulation to transmit data)**

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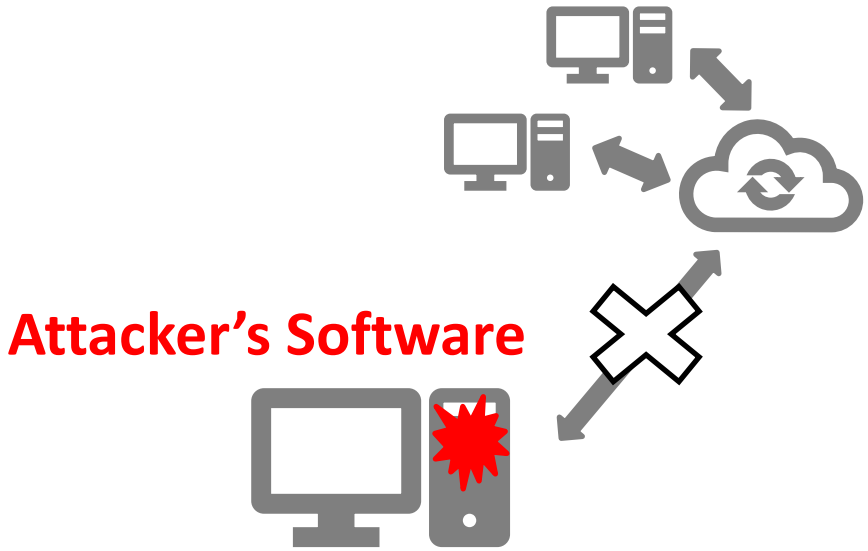
Context: Soft-TEMPEST

In theory…

Fully disconnected

Even an attacker able to execute code cannot exfiltrate data



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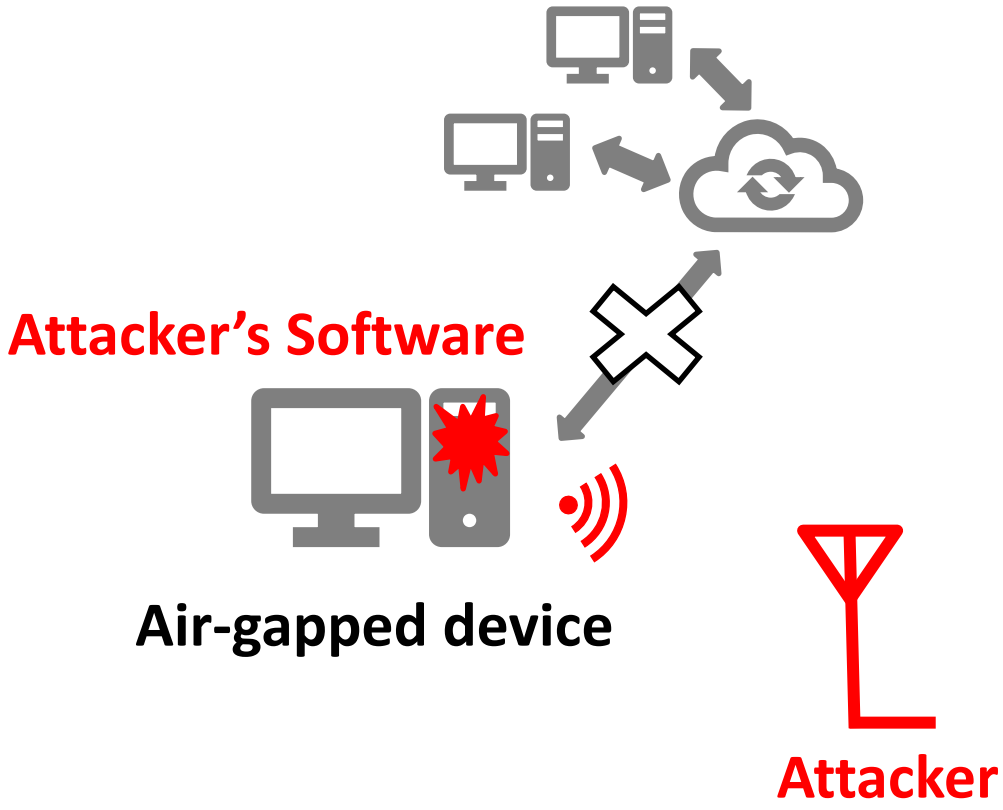
Software execution triggers and modulates EM radiation



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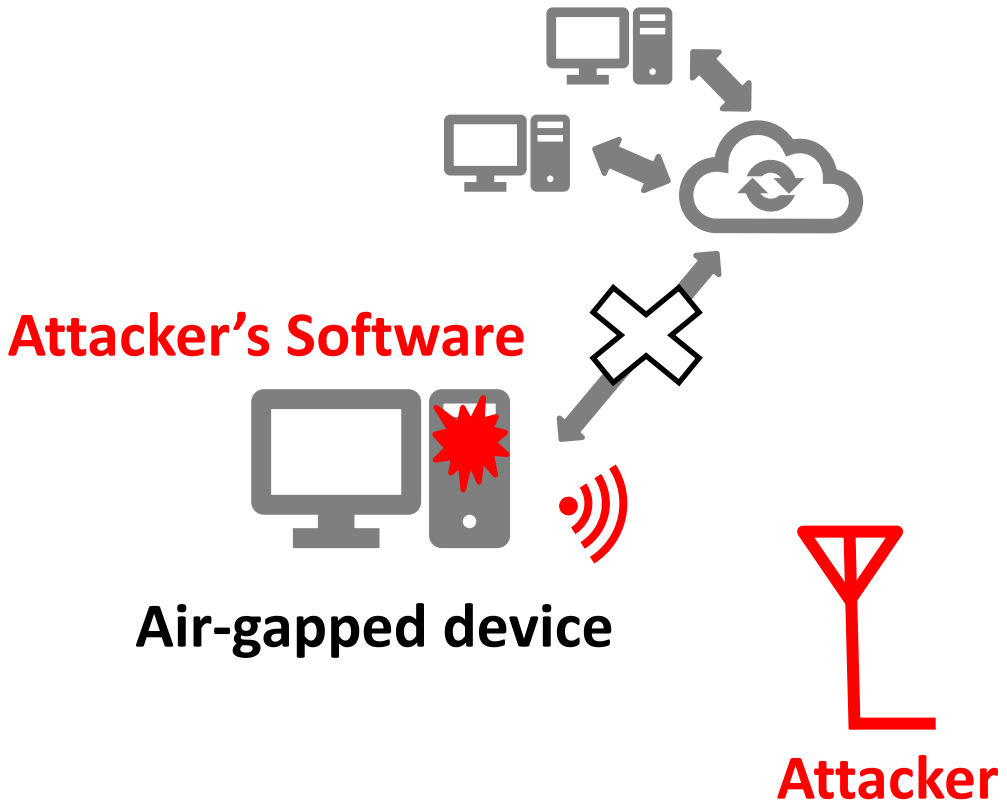
In practice…
Exfiltrate data via EM radiation
Communication is possible!



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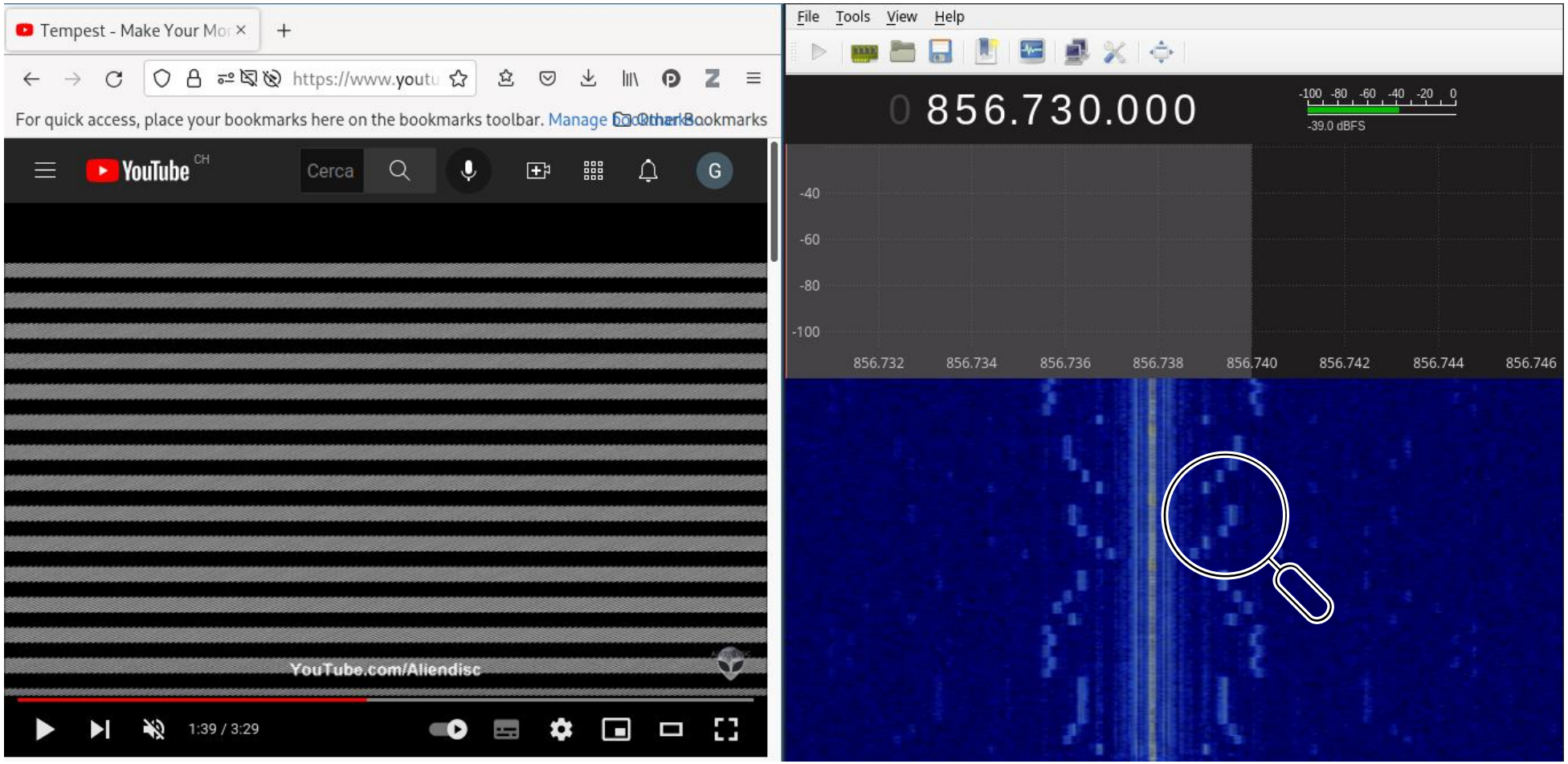
Background: the old classic "Tempest for Eliza" example



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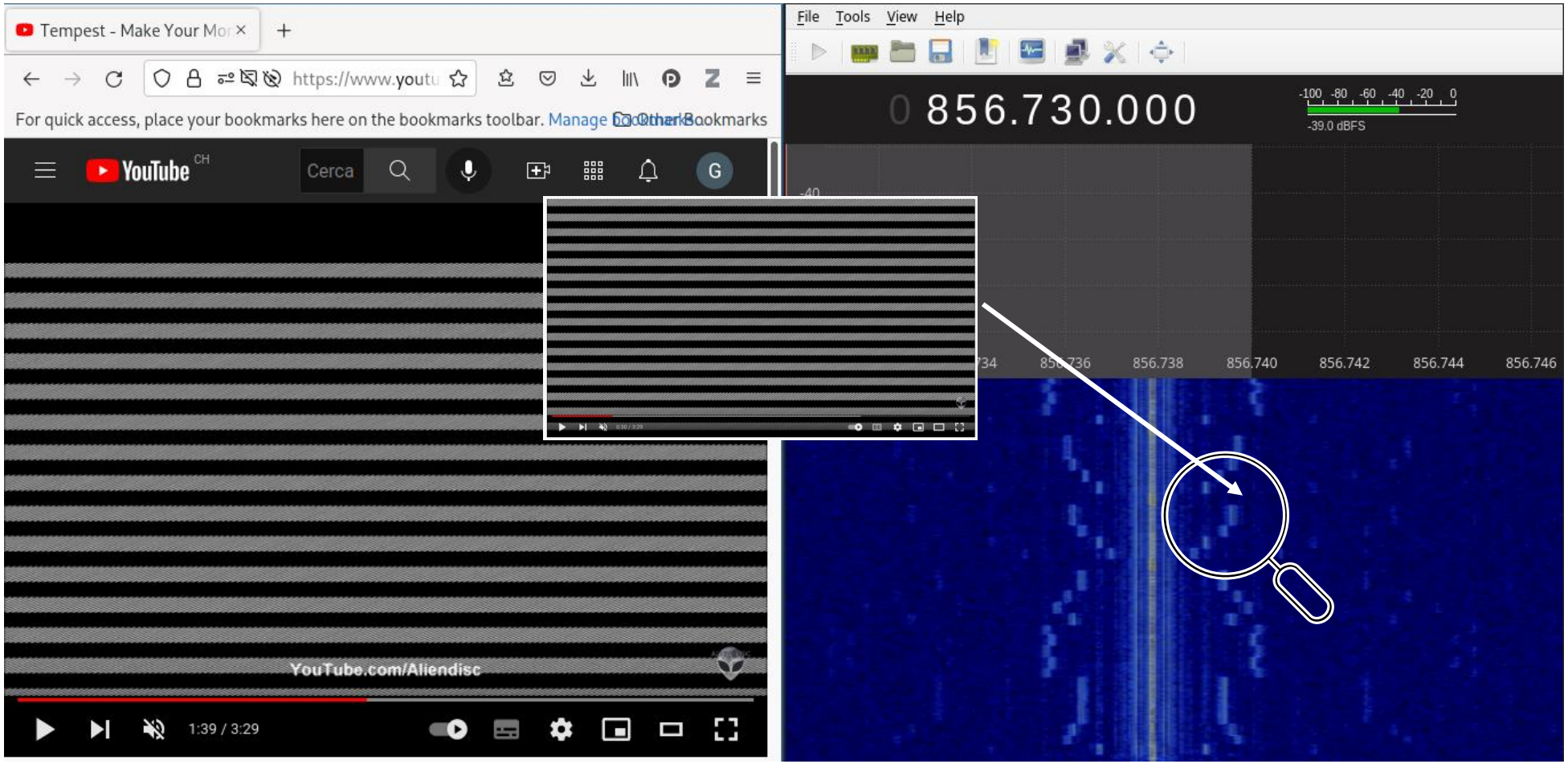

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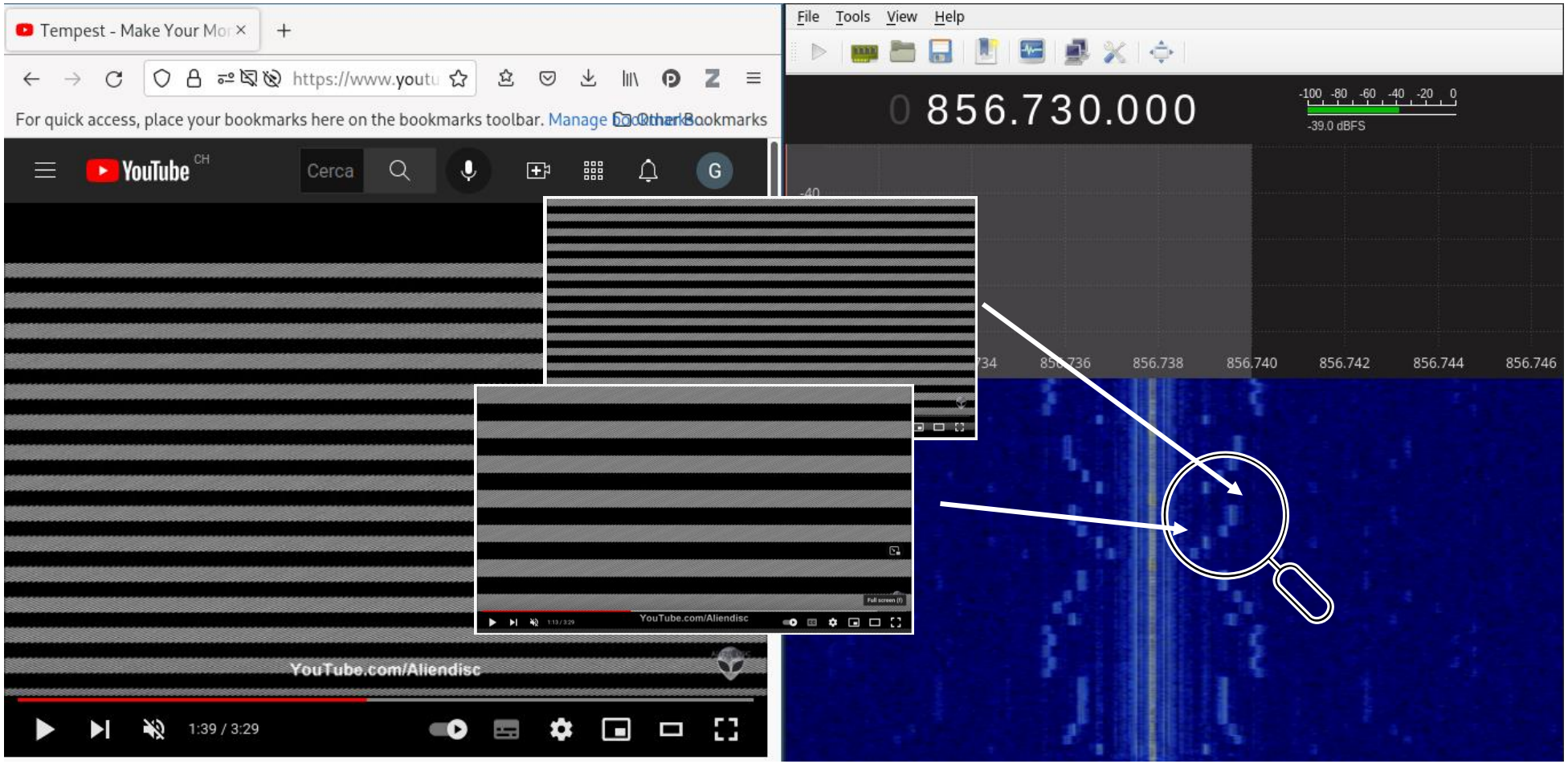

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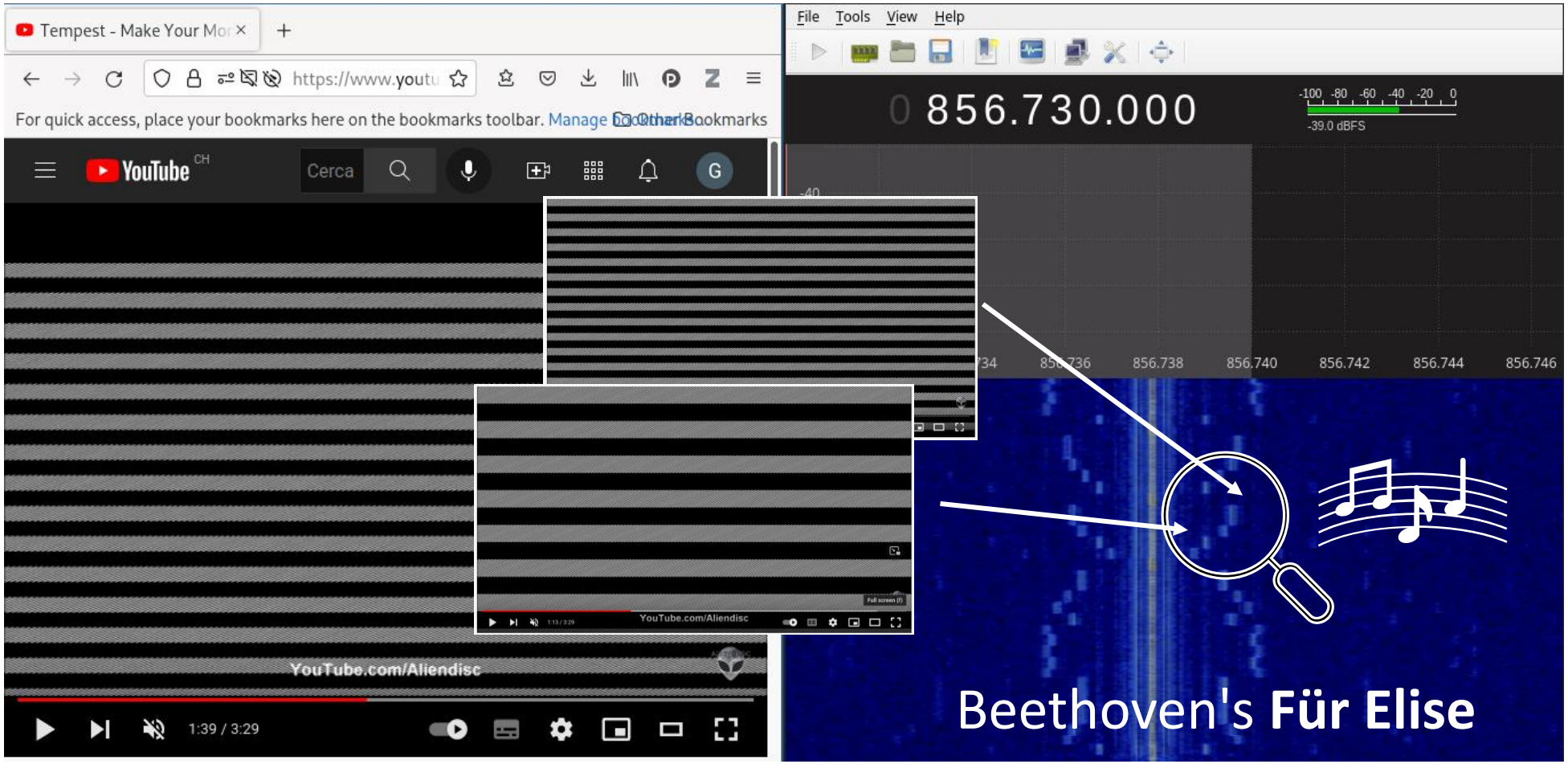

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Background: modulation 101

Carrier
Sinusoidal wave at radio frequency

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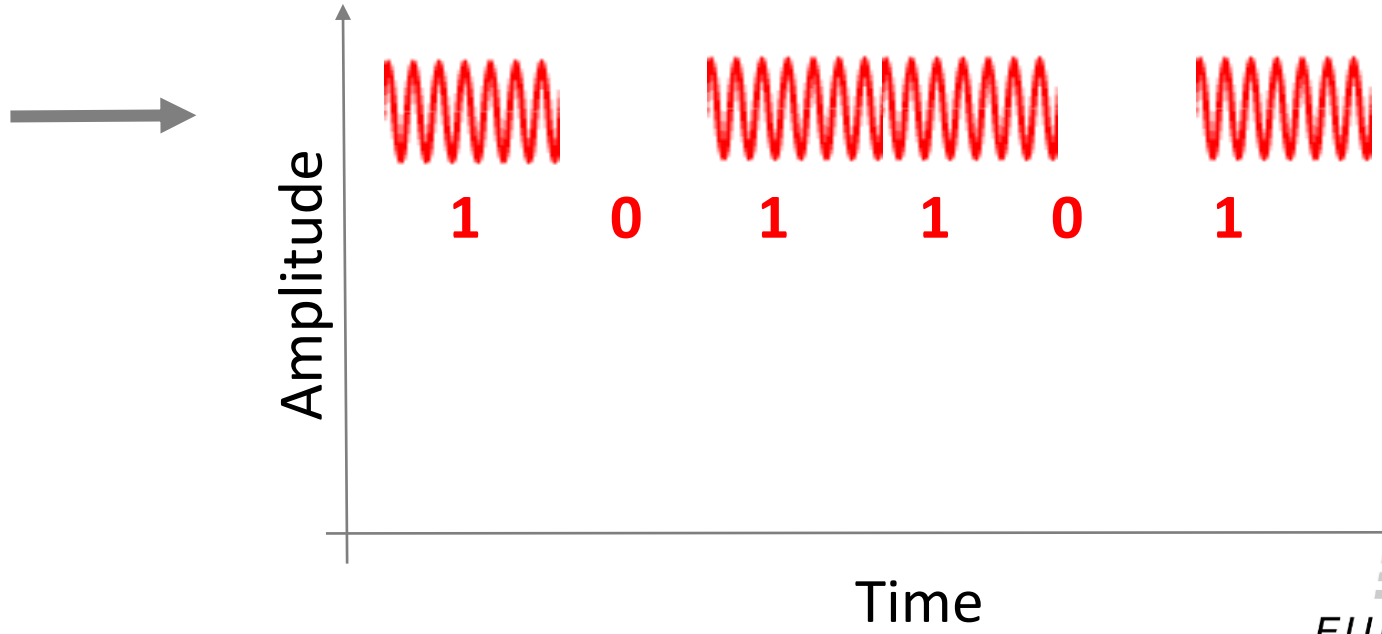
OOK
On-Off Keying



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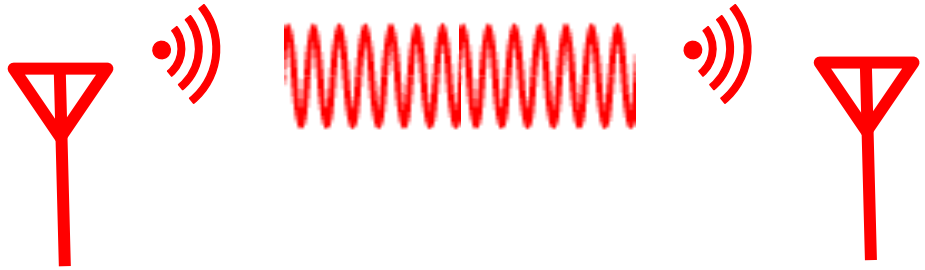
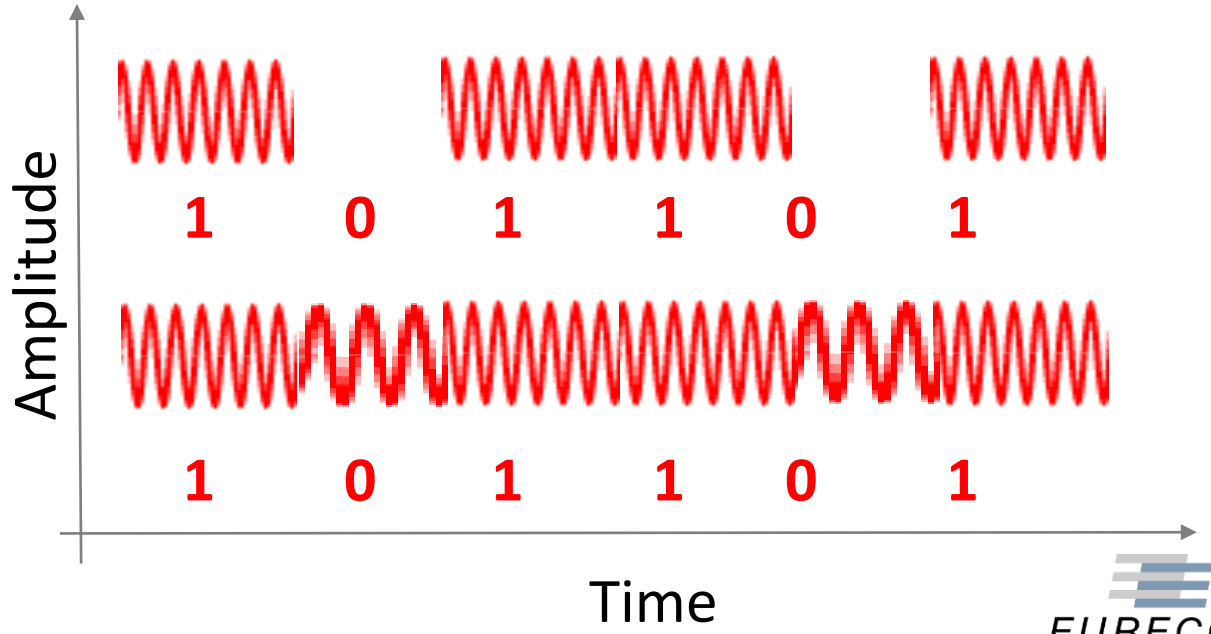


OOK
On-Off Keying

FSK
Frequency-Shift Keying



Background: general primitive in related work

```
start = now()
while( now() – start < T/2 )
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while( now() – start < T )
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Trigger leakage @$F_{leakage}$ from SW
E.g., with memory accesses*

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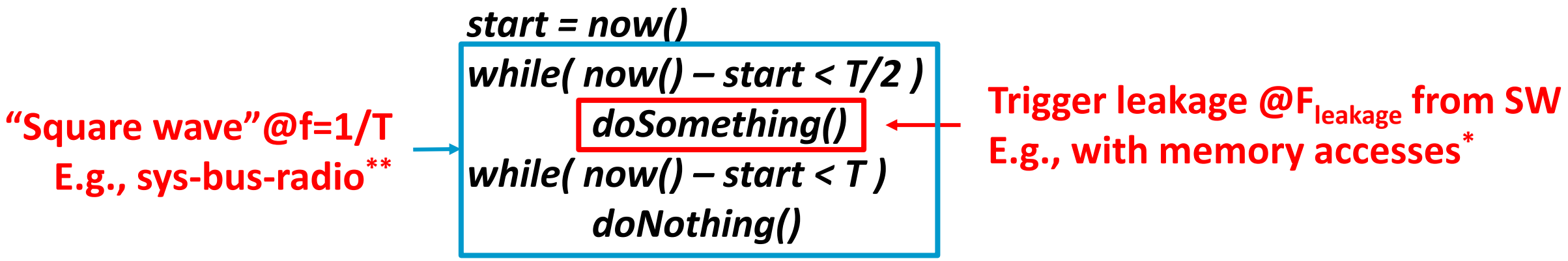

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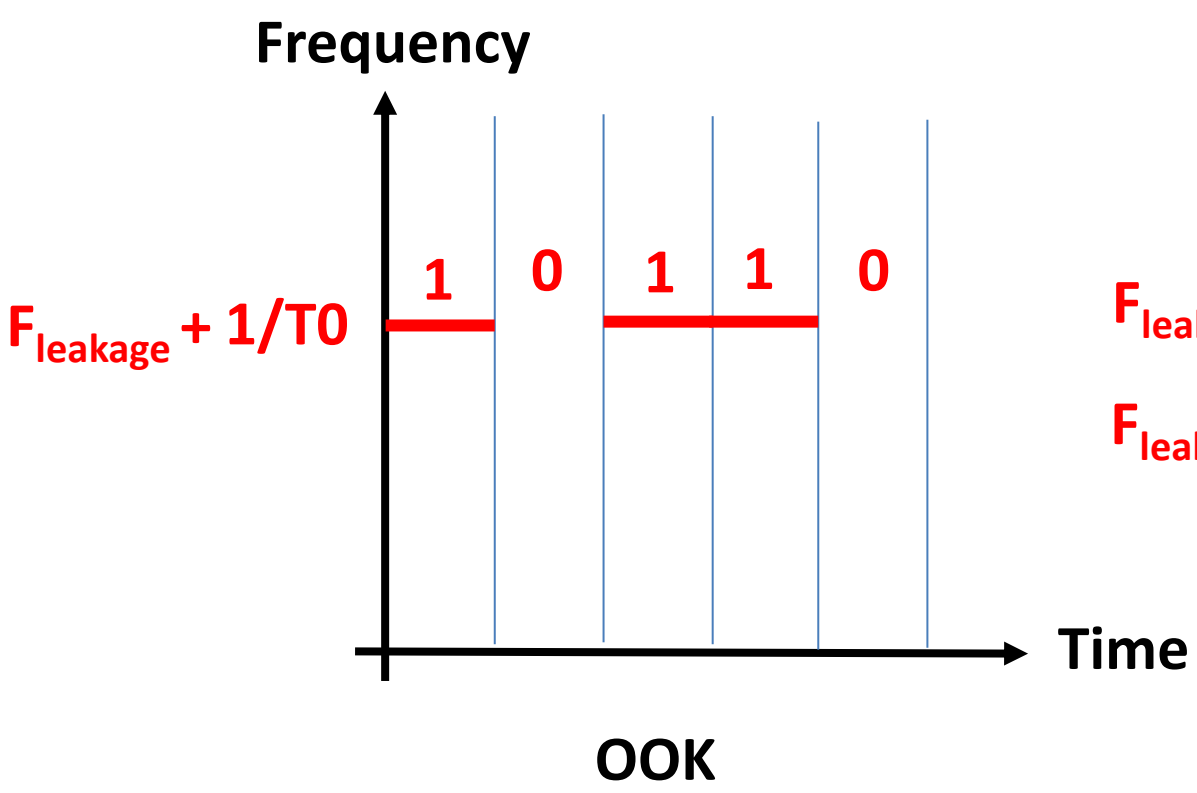

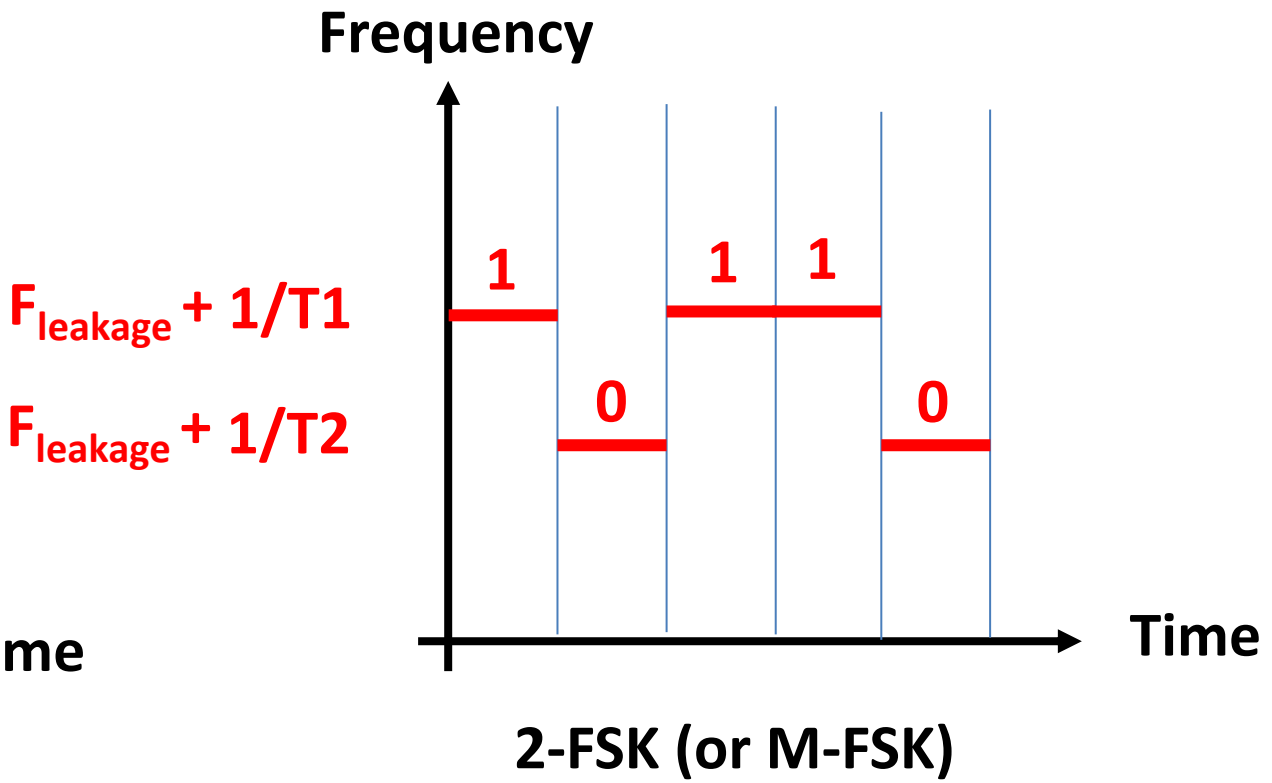

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Related work (EM)

Simple custom modulation/protocol

Name	Leakage Type	Modulation Type	Publication Venue
Soft-TEMPEST	Electromagnetic	AM, FSK	Information Hiding 1998
AirHopper	Elecromagnetic	FSK	MALWARE 2014
USBee	Elecromagnetic	FSK	PST 2016
GSMem	Elecromagnetic	OOK	USENIX Security 2015
BitJabber	Elecromagnetic	OOK, FSK	IEEE ITC 2020
MAGNETO	Magnetic	OOK, FSK	ArXiv 2018
ODINI	Magnetic	OOK-(many cores), FSK	IEEE Trans. Inf. Forensics Secur. 2020
Matyunin et. al	Magnetic	OOK, FSK	ASP-DAC 2016
EMLora	Electromagnetic	CSS	IEEE S&P 2021

A first step towards more advanced modulation

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Limitations of previous work

Simple custom modulation

Mostly simple OOK or FSK, generally requires custom receivers

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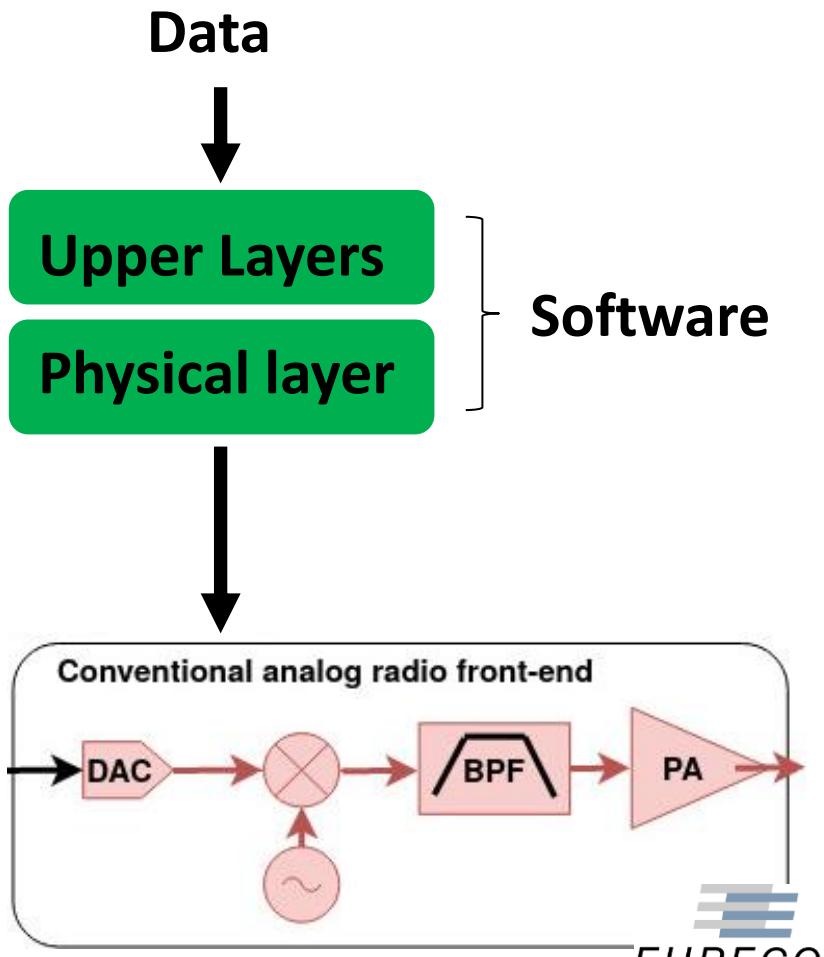
Single application
Exfiltration from air-gapped devices

Meanwhile the (real) software-defined radios...

Software-defined
Signals entirely defined in software
Minimal hardware to create the actual waves



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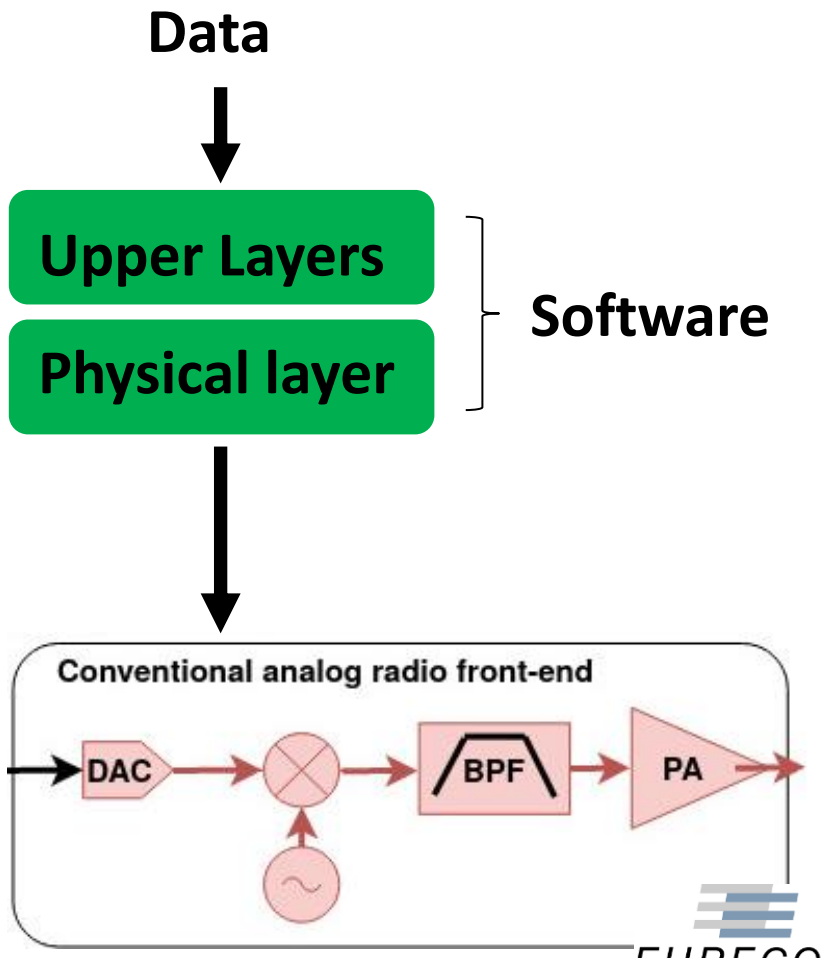
Arbitrary modulation
Can shape generic signals
Advanced modulation techniques possible



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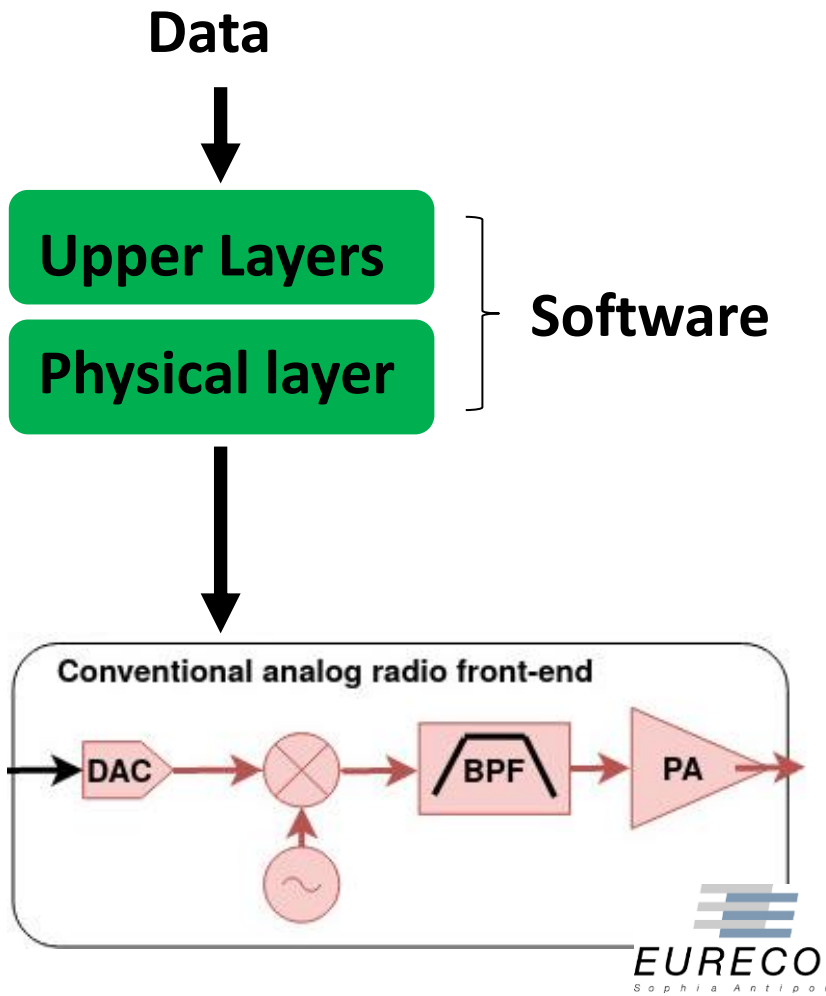

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Advanced protocols
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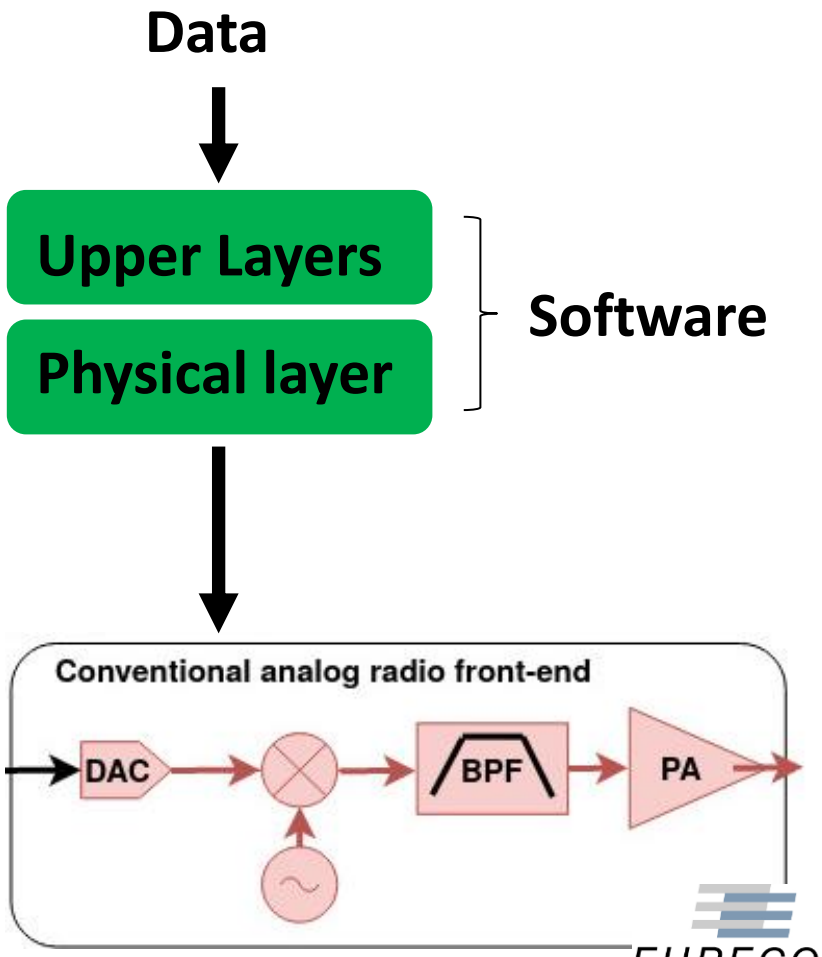
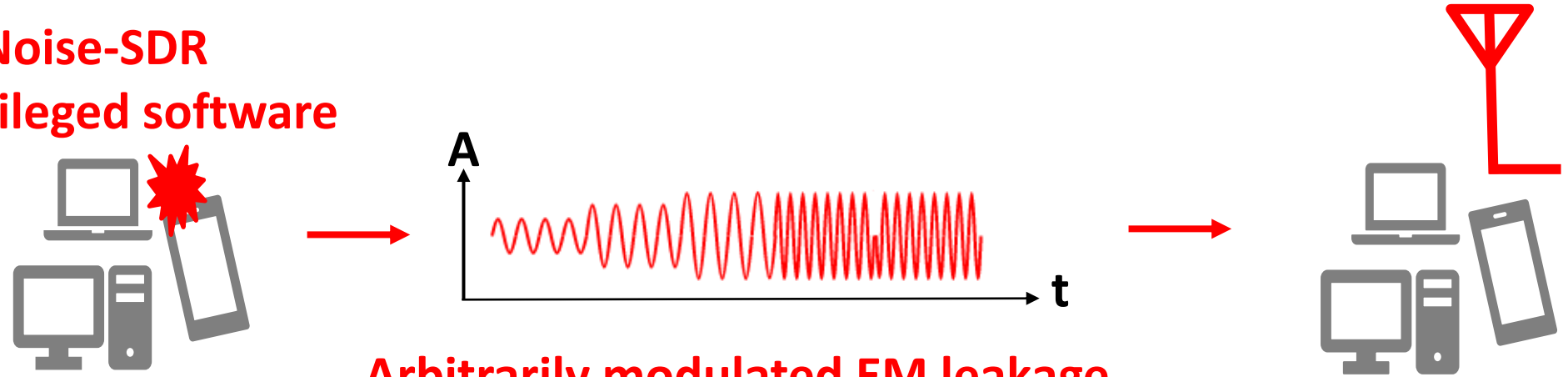
Flexible
Can handle virtually any protocol / application



Can we do more with Soft-TEMPEST?

Goal: Can we do more?

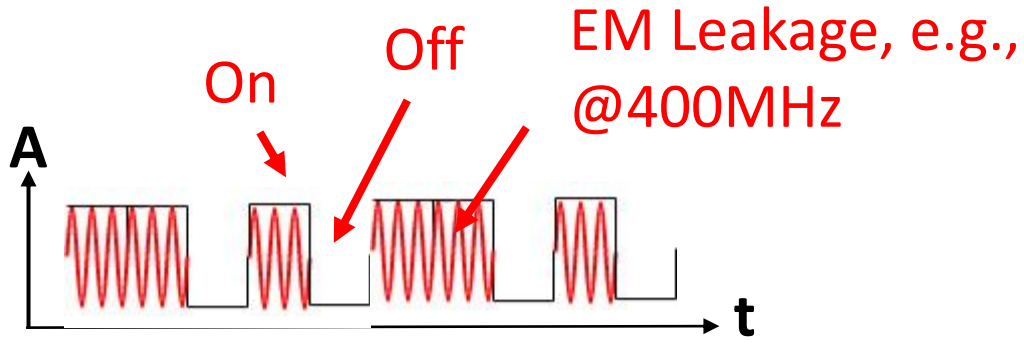
Noise-SDR
Unprivileged software



Arbitrarily modulated EM leakage

- **+ Software-defined:** flexibility, existing protocols
- **+ Advanced PHY layer:** performance
- **+ More applications:** exfiltration, tracking, injection, …

Challenge: from square wave to generic passband signal



Unprivileged software:

1. **DRAM access:** “EM leakage ON”
2. **Do nothing:** “EM leakage OFF”

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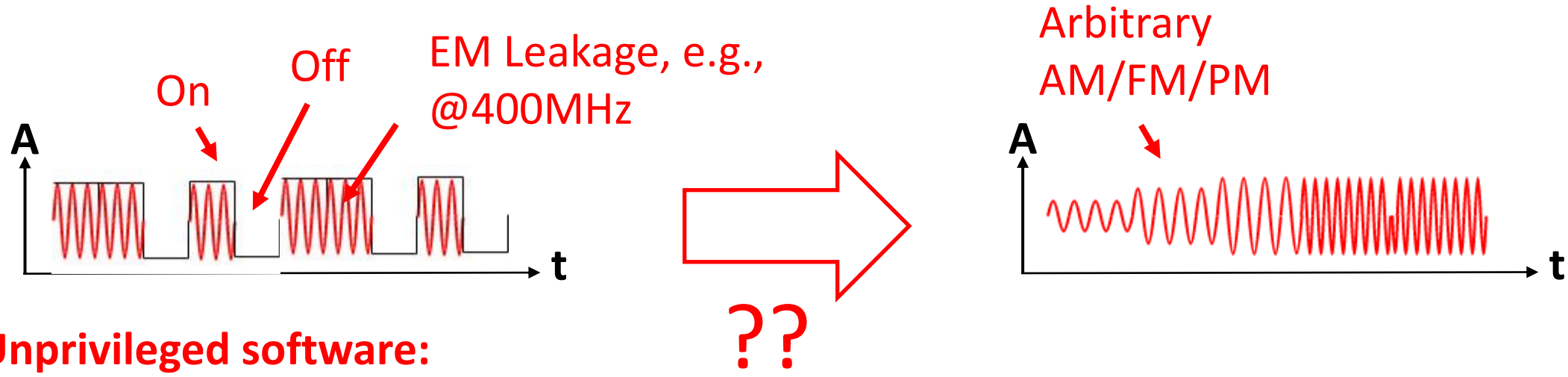

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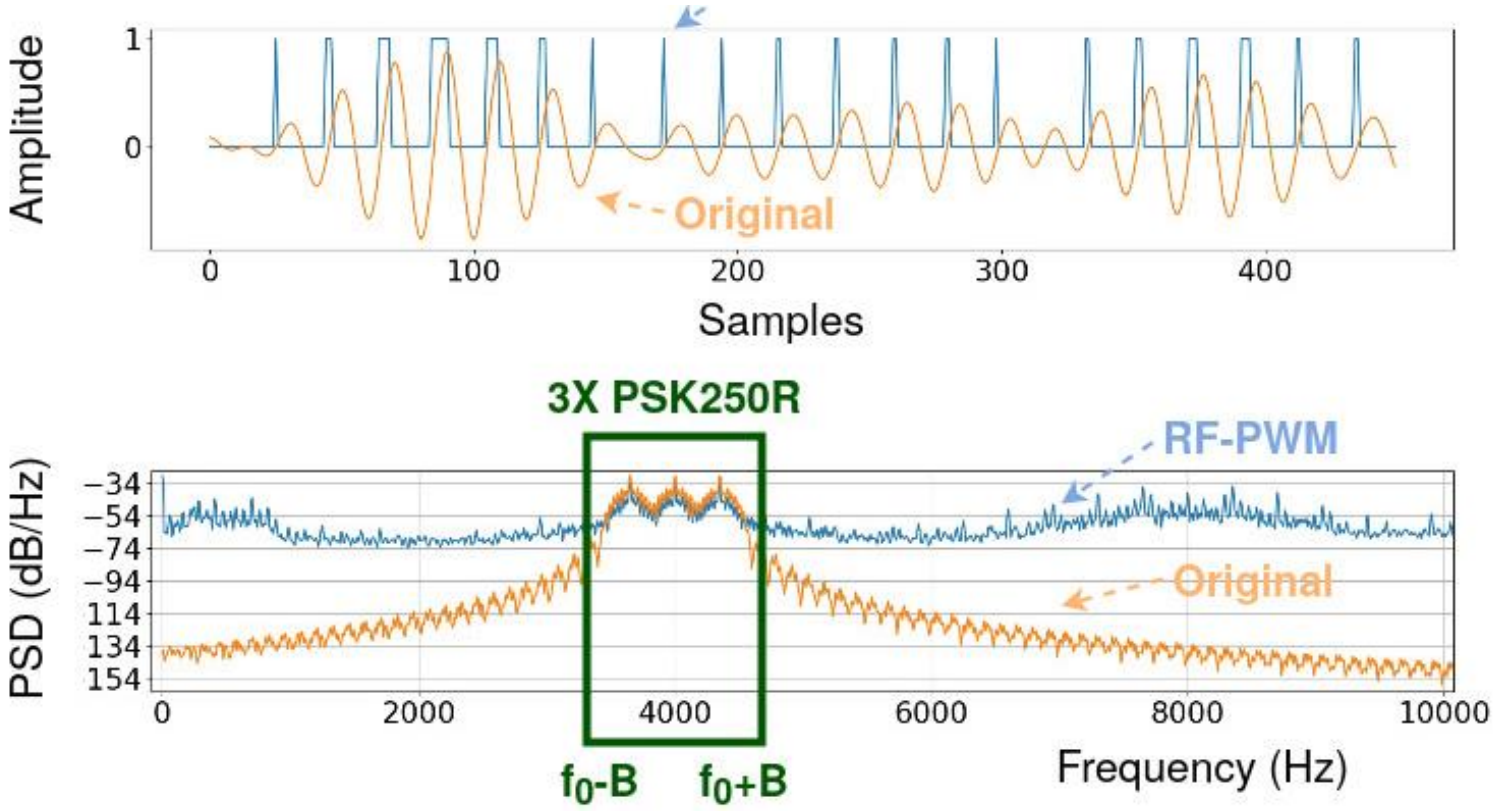
Solution: leverage pass-band one-bit coding (RF-PWM)

Long story short: approximate a modulated sine-wave with a square wave



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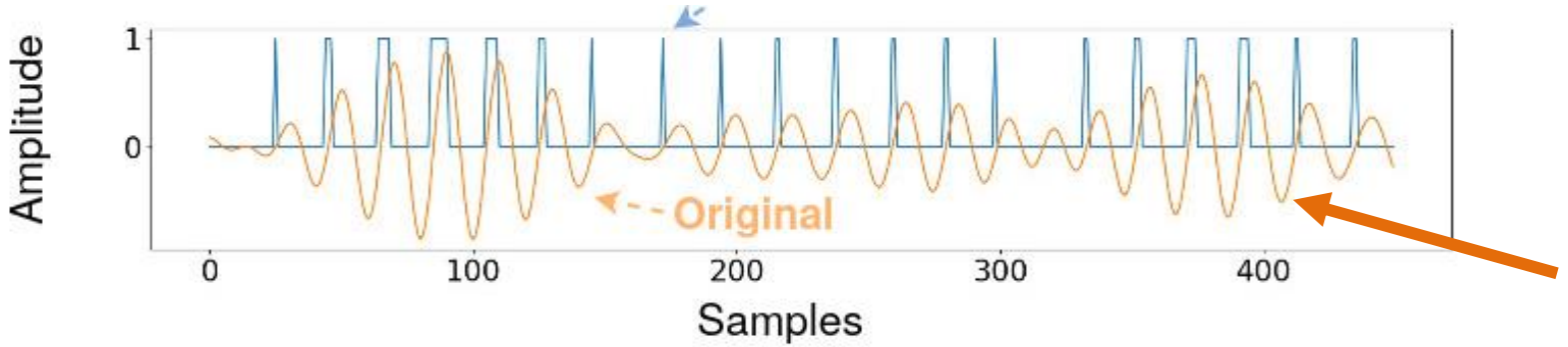
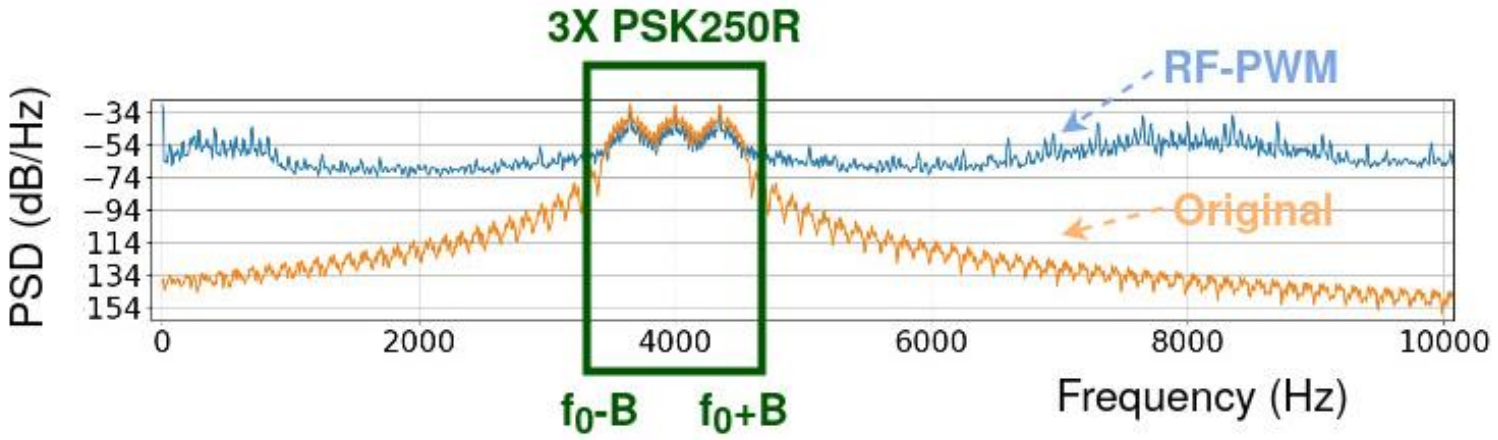


Goal:
3xPSK250R



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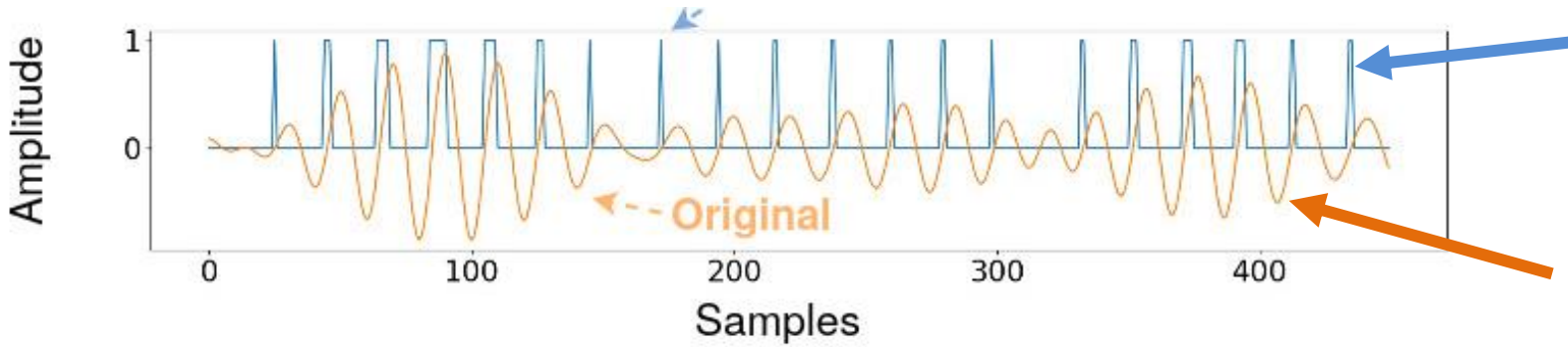

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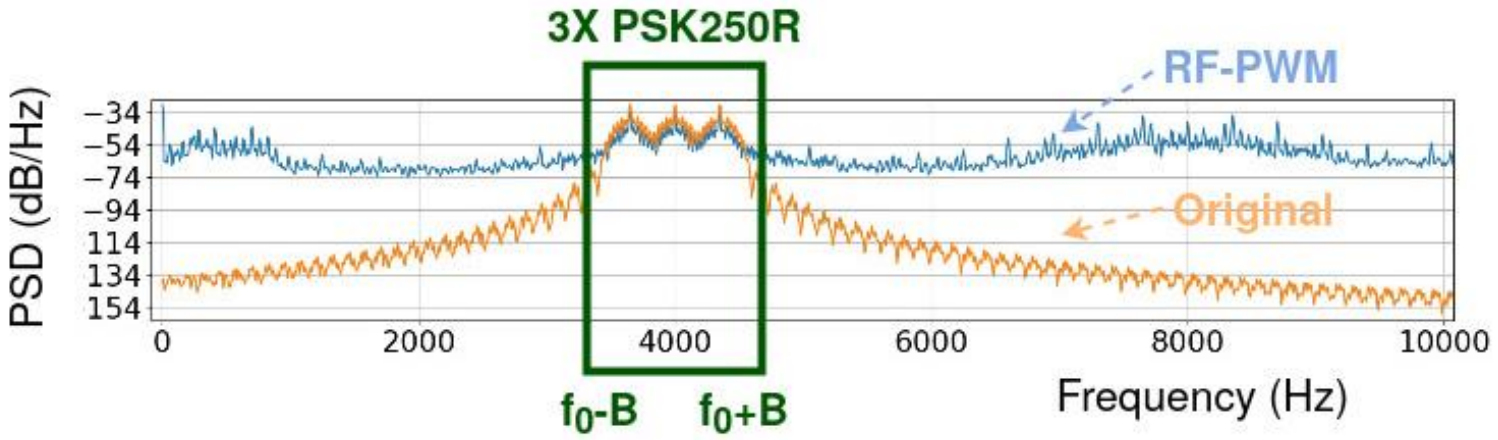

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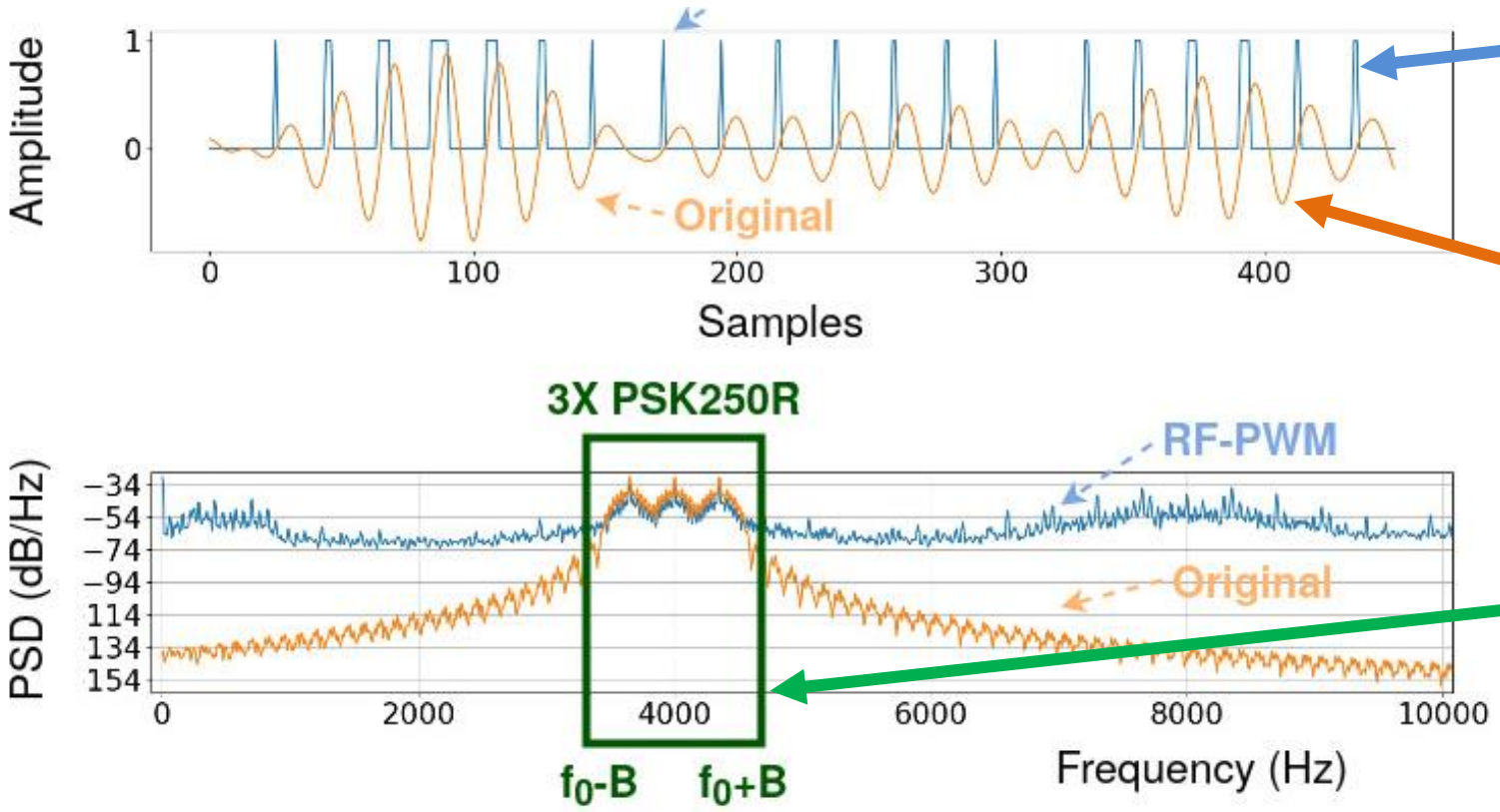

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Band of interest:
Good approximation

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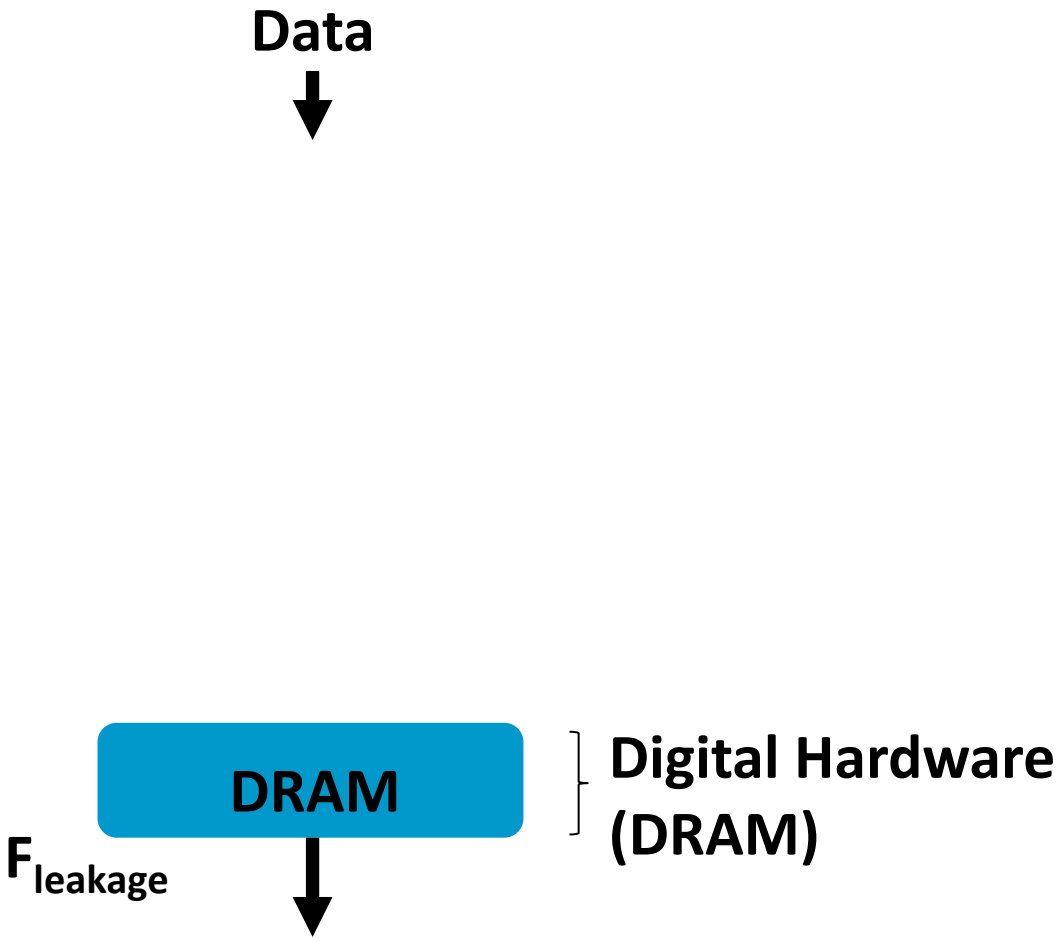
Noise-SDR: Arbitrary Modulation of EM noise



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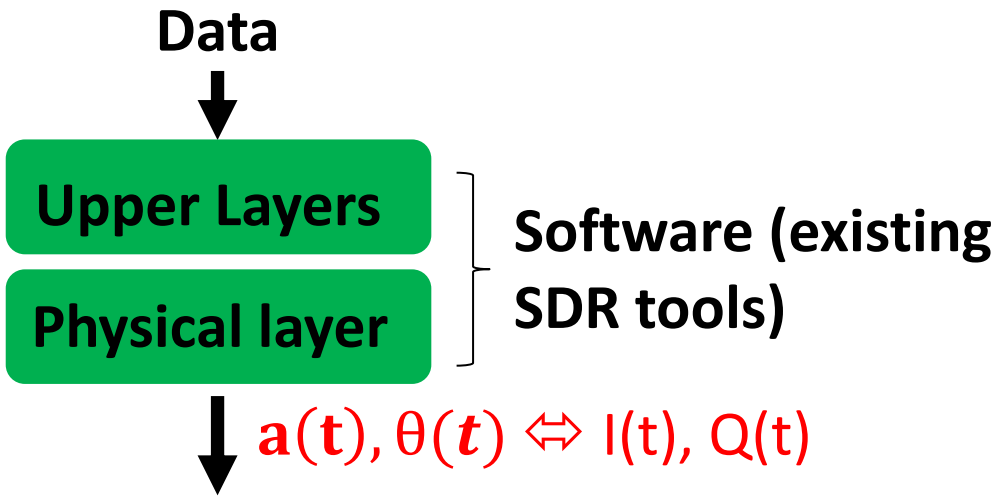

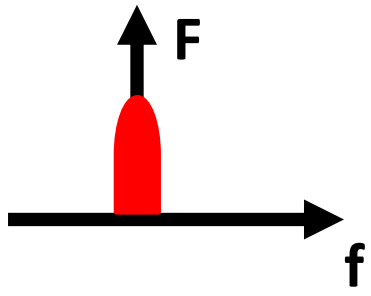

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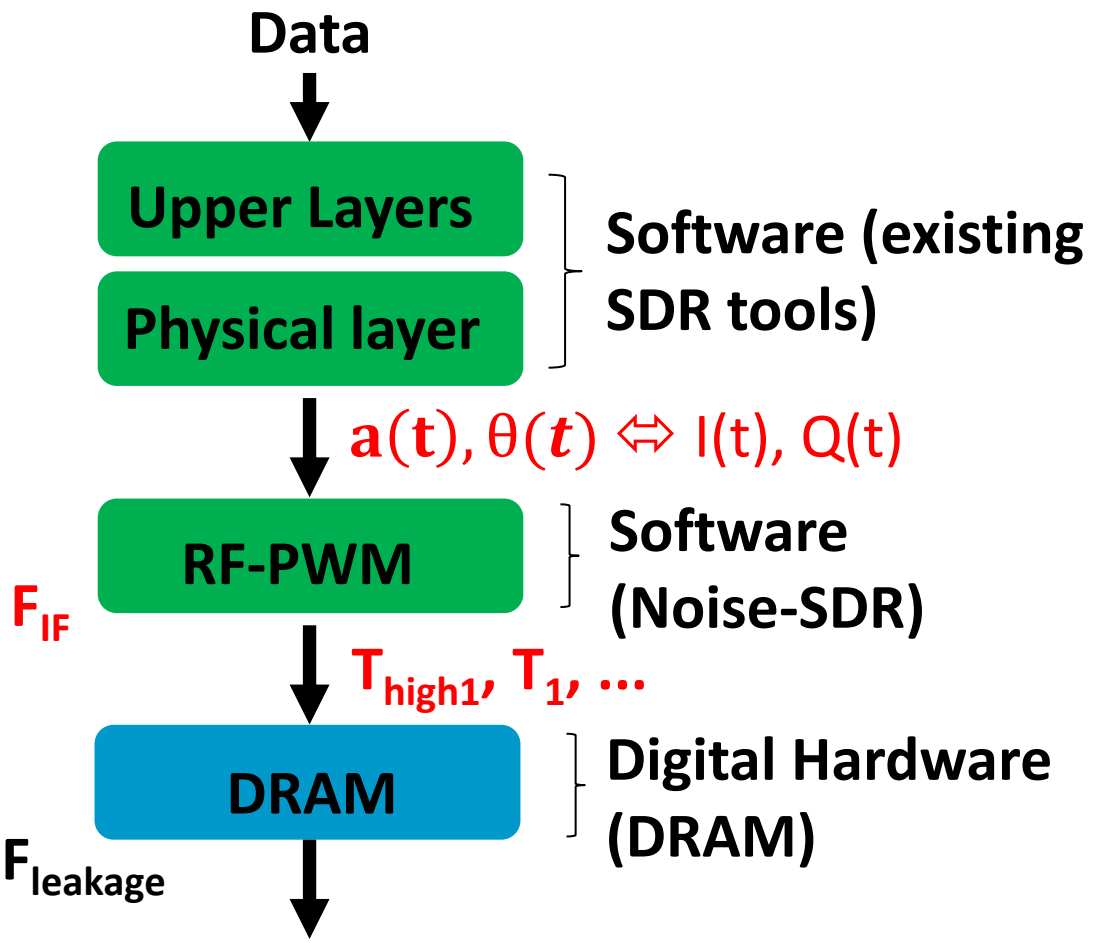

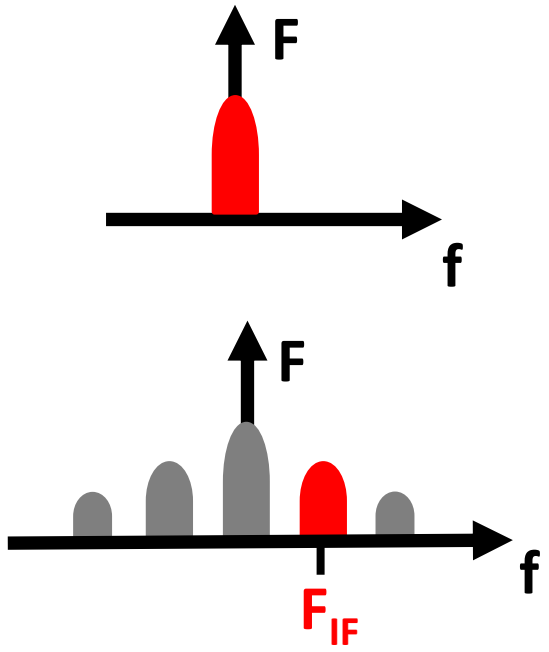

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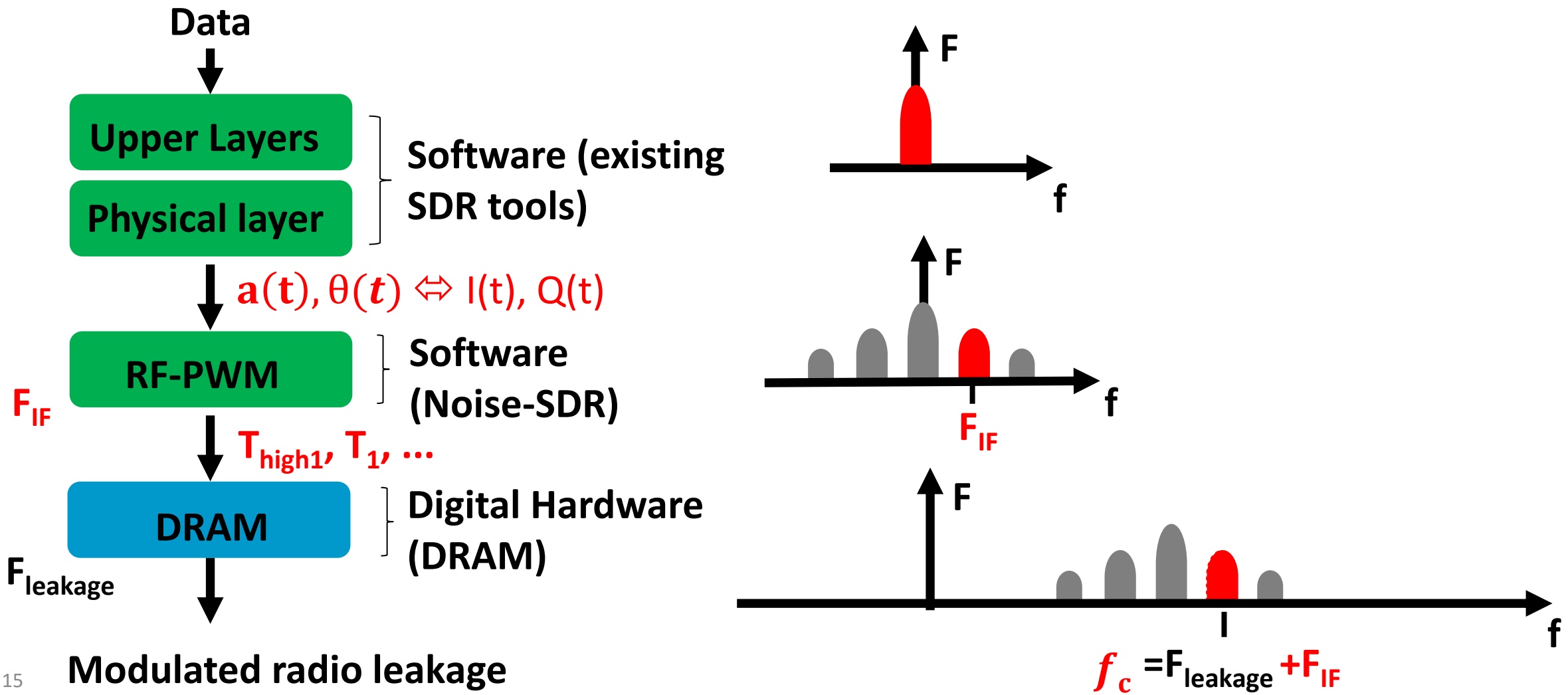
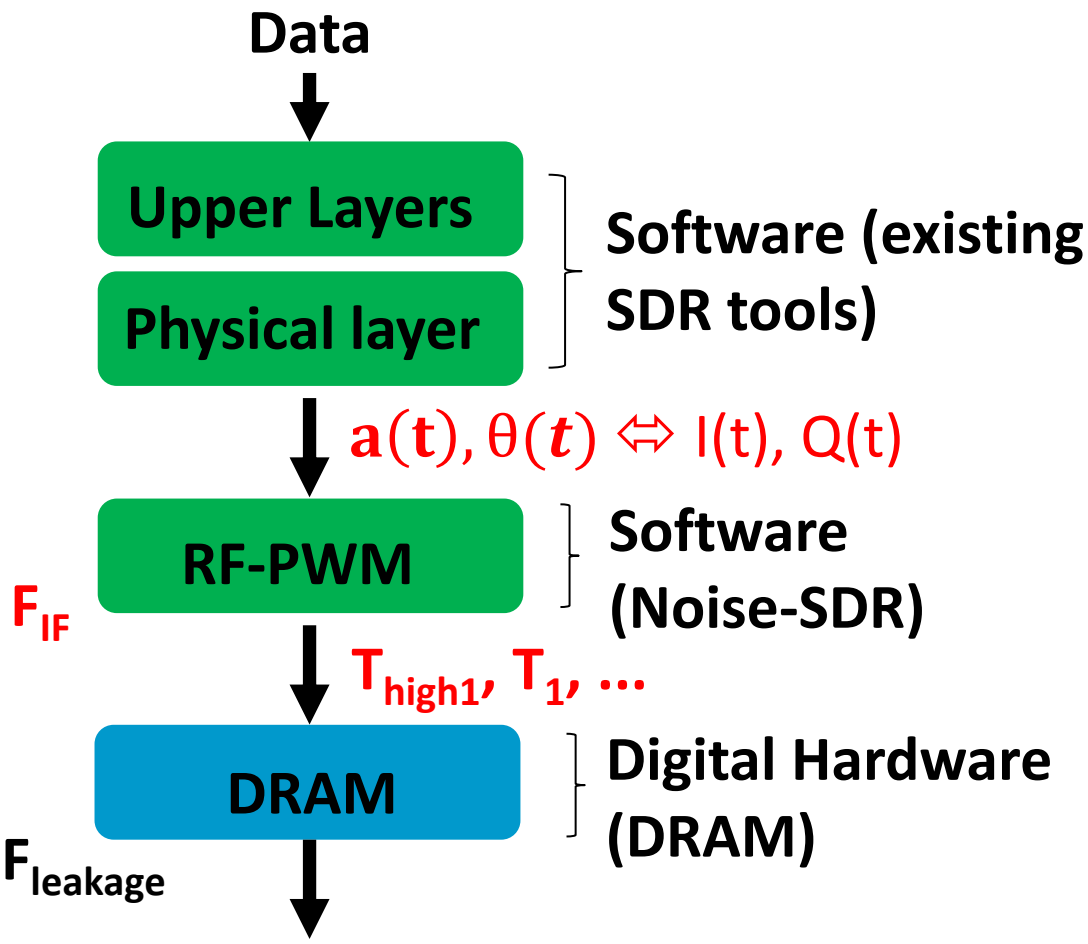
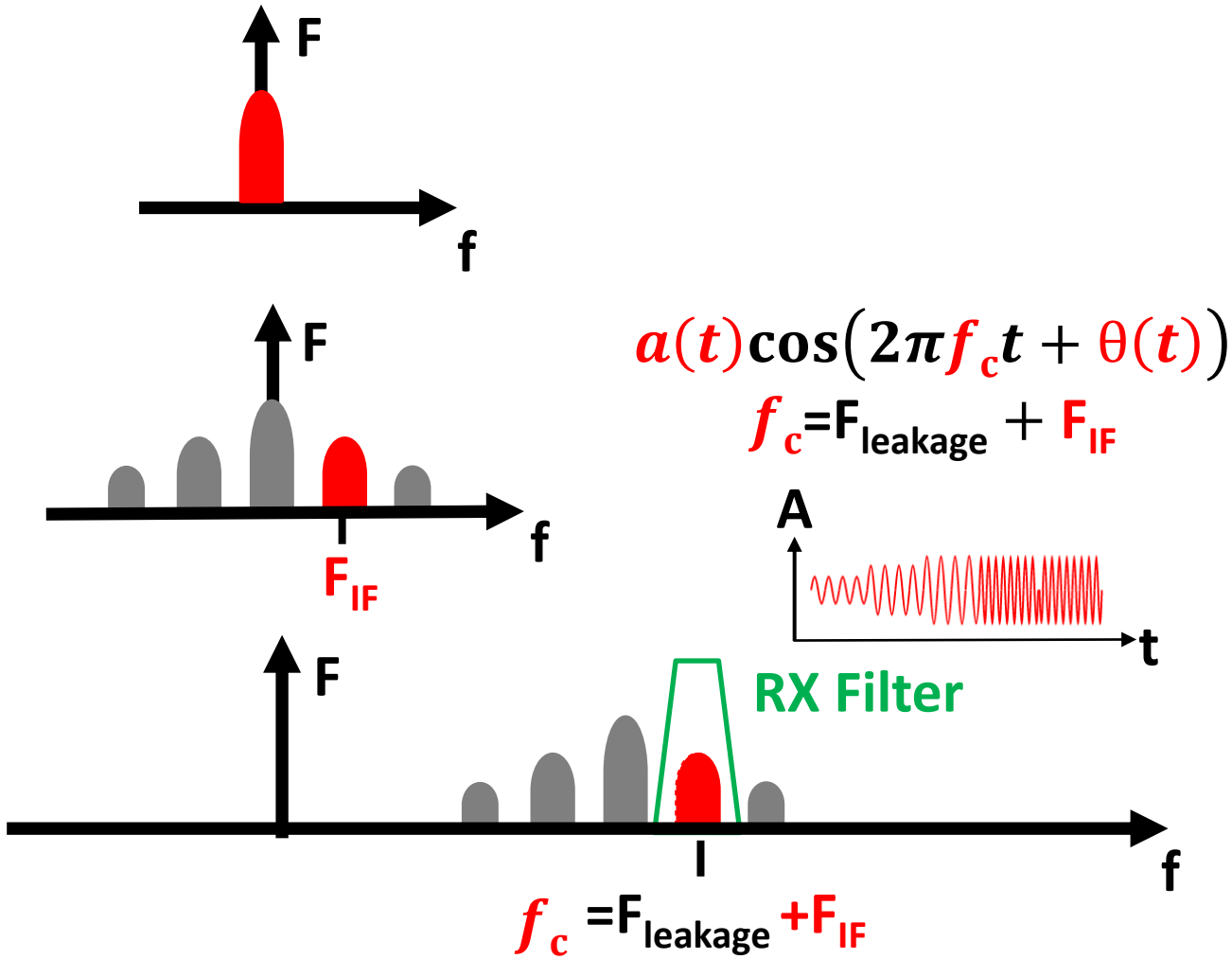


Noise-SDR: Arbitrary Modulation of EM noise



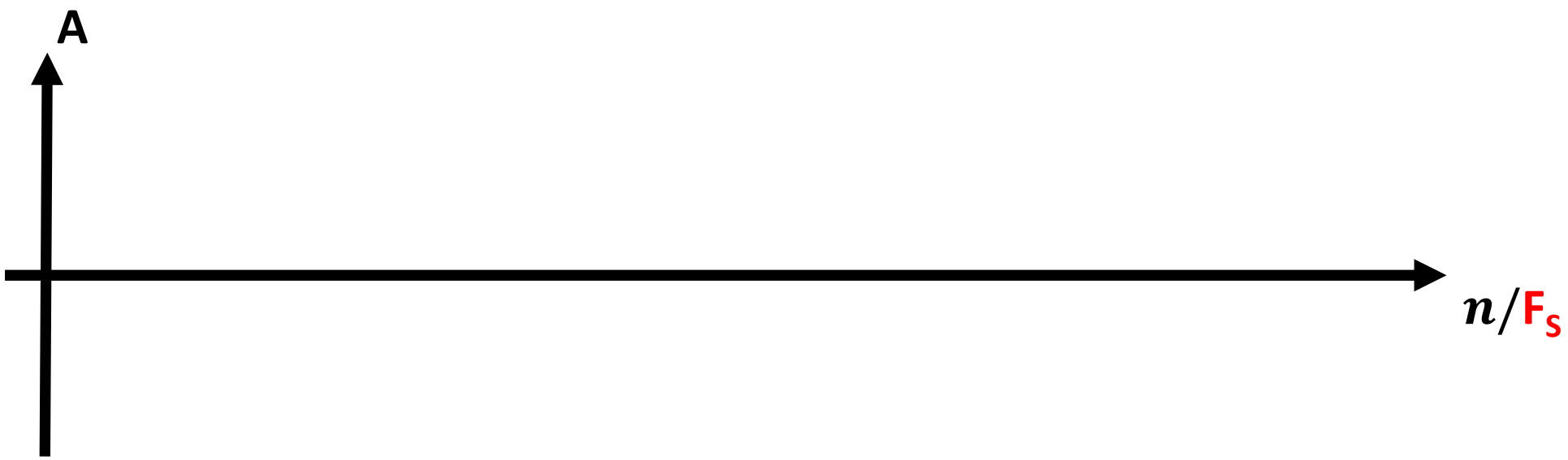


How do we implement it in practice?

Implementation: discrete-time RF-PWM

Input: F_S, $a(n/F_S)$, $\theta(n/F_S)$, F_{IF}

Simplified explanation



Output:

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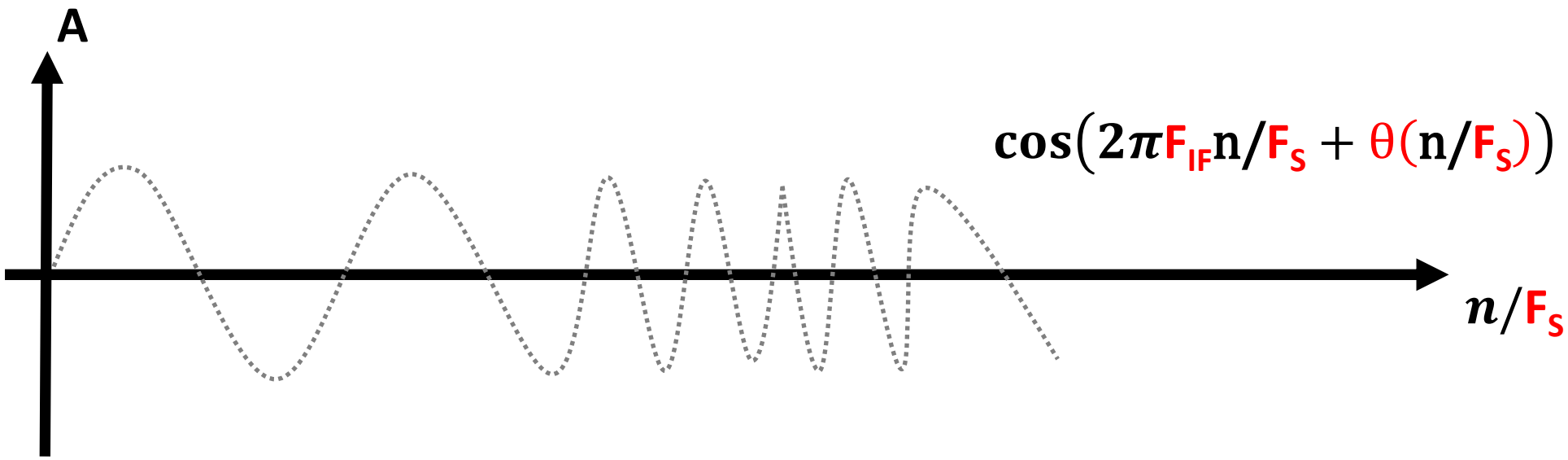

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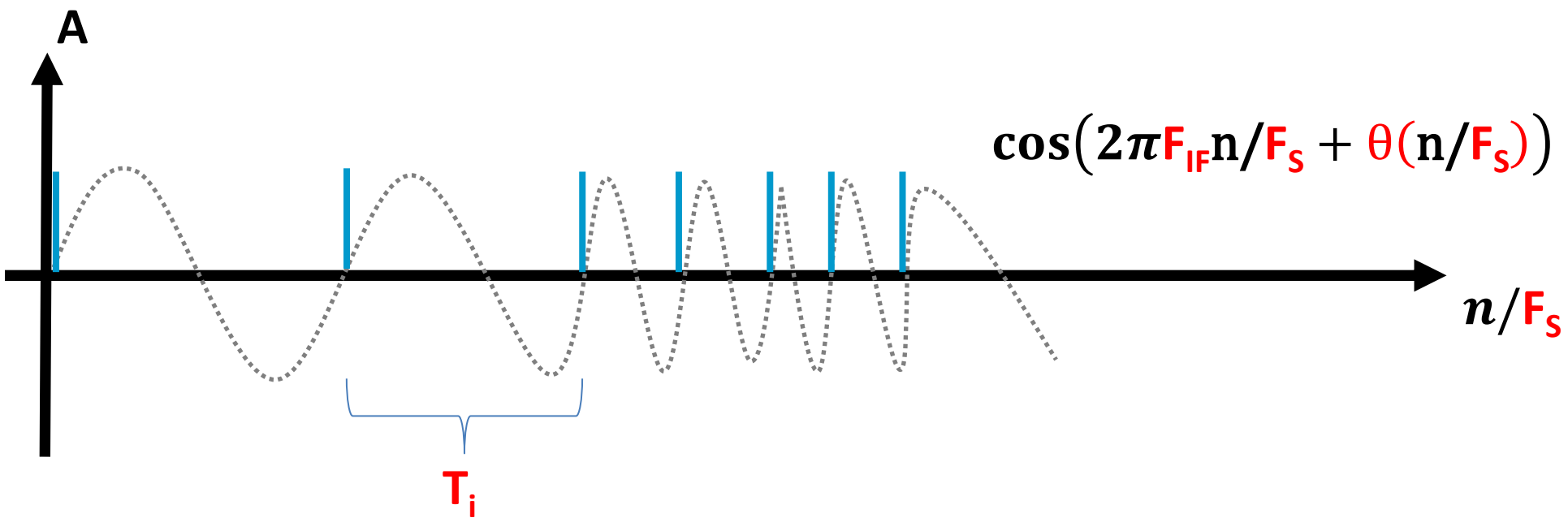

Output: T_1, T_2, T_3, ...

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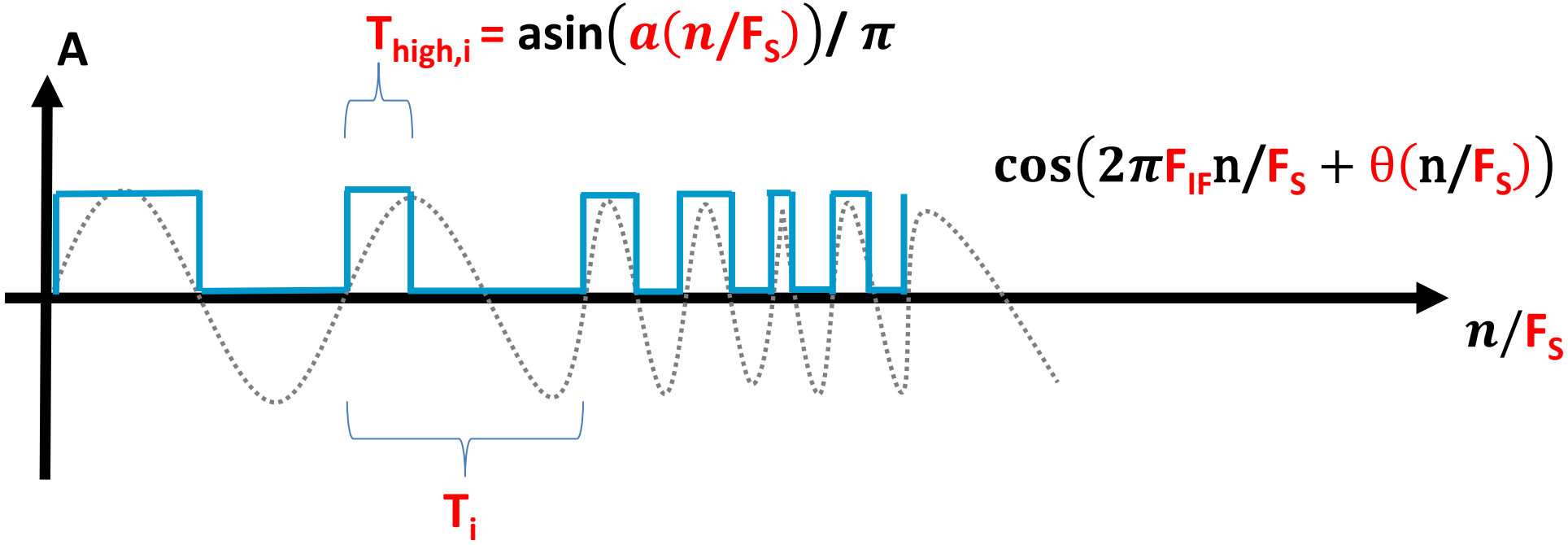

Output: $T_{high,1}$ T_1, $T_{high,2}$ T_2, $T_{high,3}$ T_3, ...

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Implementation: software-control

```
start = now()
while( now() – start < T_high,i )
        leakyOperation()
while( now() – start < T_i )
        doNothing()
```

Time accuracy is fundamental!
(Bandwidth, am/fm/pm quantization)

*M. Schwarz et al., “Fantastic Timers and Where to Find Them: High-Resolution Microarchitectural Attacks in JavaScript,” in FC 2017.

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Leaky, fast*****

Many in the paper and in general

E.g., on Arm-v8 (re)use ROWHAMMER

```
__attribute__((naked)) \
void hammer_civac(uint64_t *addr) {
  __asm volatile("LDR X9, [X0]");
  __asm volatile("DC CIVAC, X0");
  __asm volatile("DSB 0xB");
  __asm volatile("RET");
}
```

*M. Schwarz et al., “Fantastic Timers and Where to Find Them: High-Resolution Microarchitectural Attacks in JavaScript,” in FC 2017.

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Implementation: combine Noise-SDR with popular SDR tools

Fldigi-Noise-SDR

> ./fldigi-noise-sdr -I secret.txt -m MODE_3X_PSK250R –c 4000

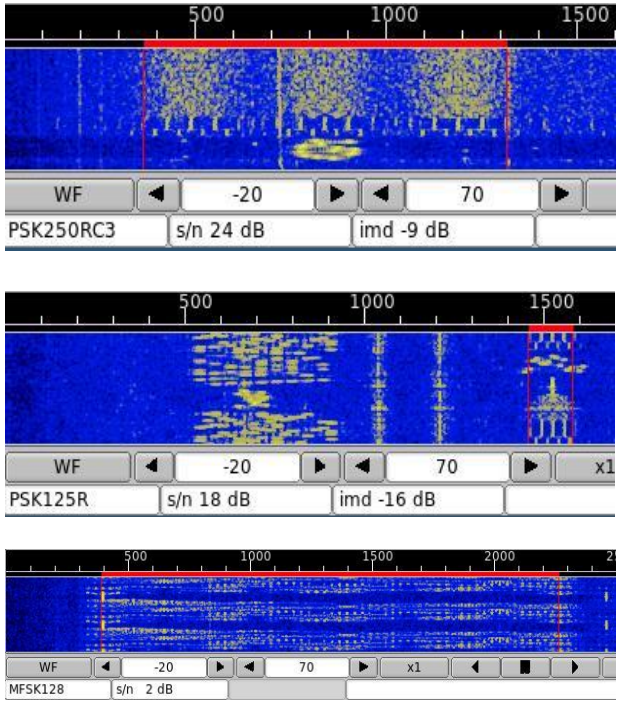
Or **Gnuradio+RF-PWM+Offline-Noise-SDR**

>./rfpwm.py ft4.iq ft4.timings
>./offline-noise-sdr ft4.timings

Evaluation

Noise-SDR in action: a few examples

More videos: https://github.com/eurecom-s3/noise-sdr



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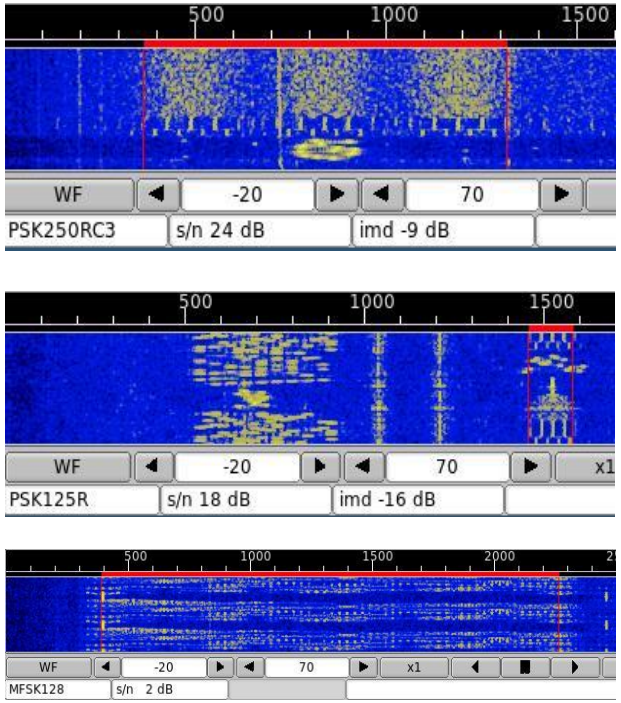

Pros

1. Software-defined, flexible
2. AM, FM, PSK, RTTY, THOR, SSTV, LoRa, GLONASS C/A, etc.
3. ArmV7A, ArmV8A, x86, MIPS
4. Mobile/desktop/laptop/IoT

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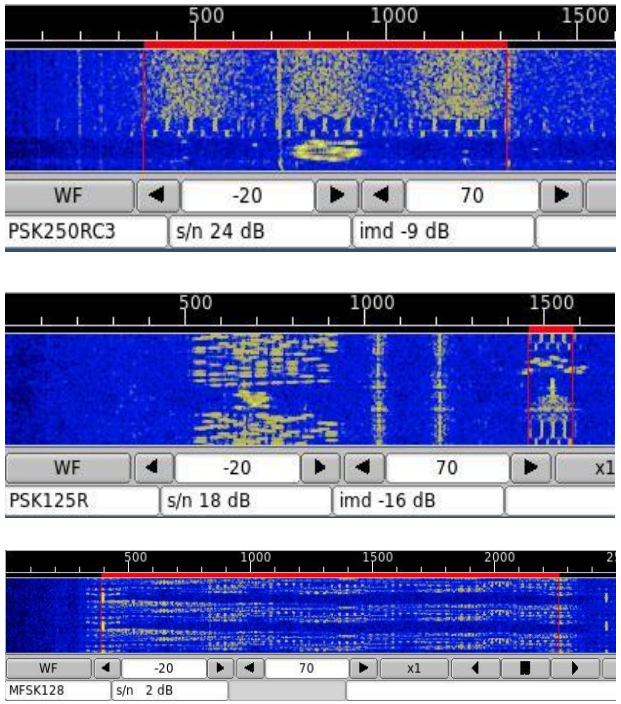

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4. Mobile/desktop/laptop/IoT

Limitations

1. There must be a leakage (device dependent)
2. Limited bandwidth
3. Limited choice of carrier frequency

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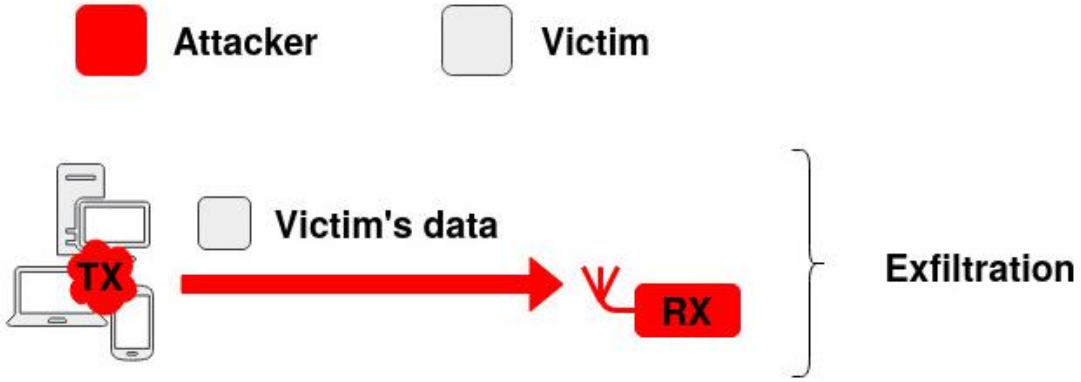
Security Impact

Security impact: exfiltration, tracking, injection



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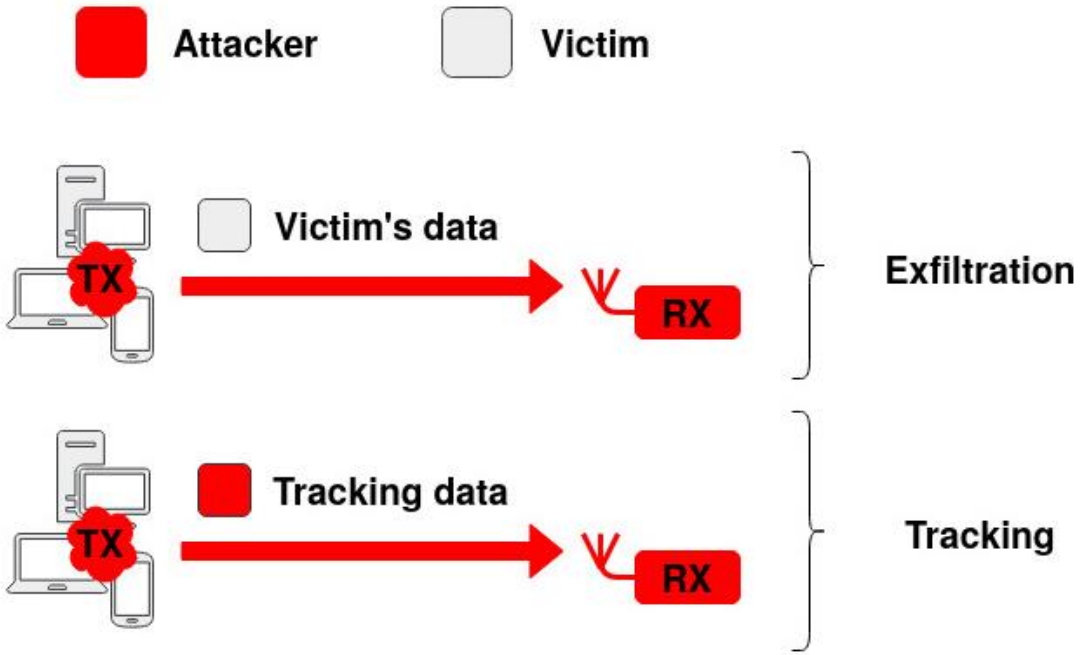

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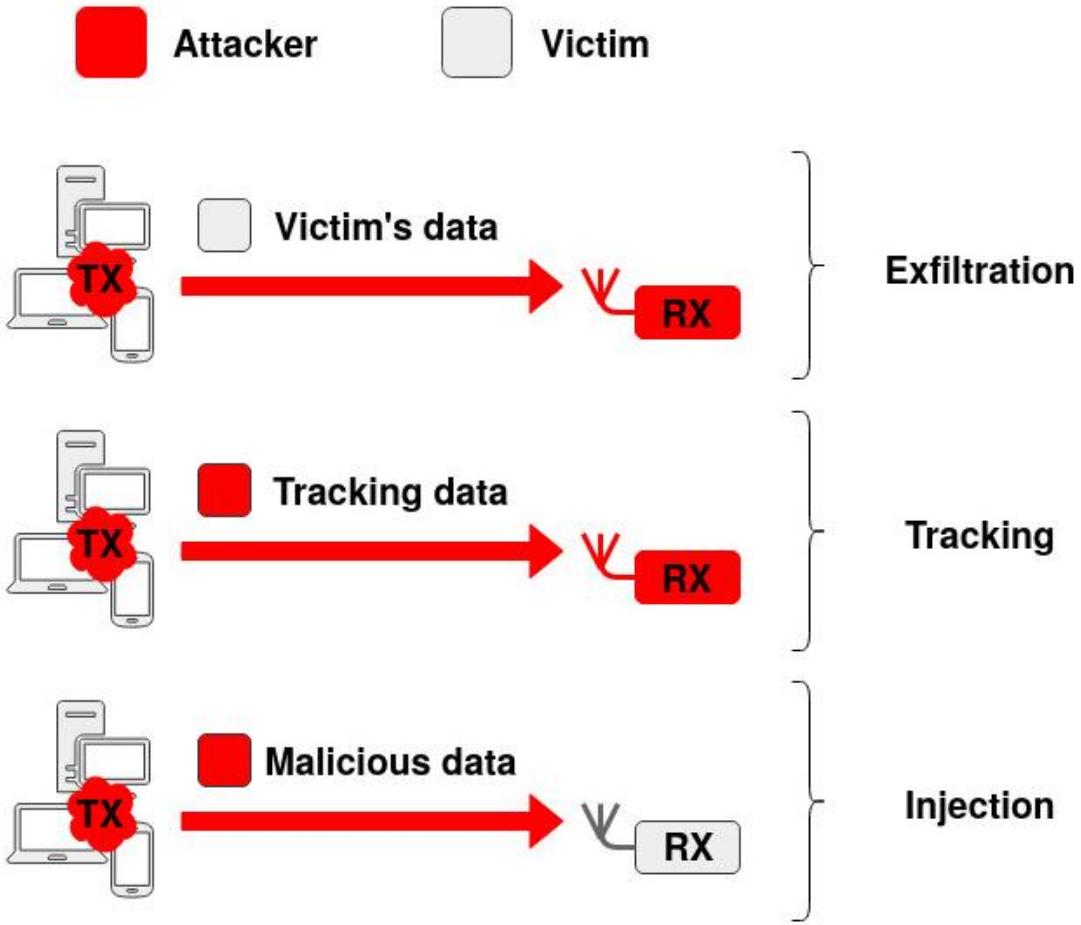

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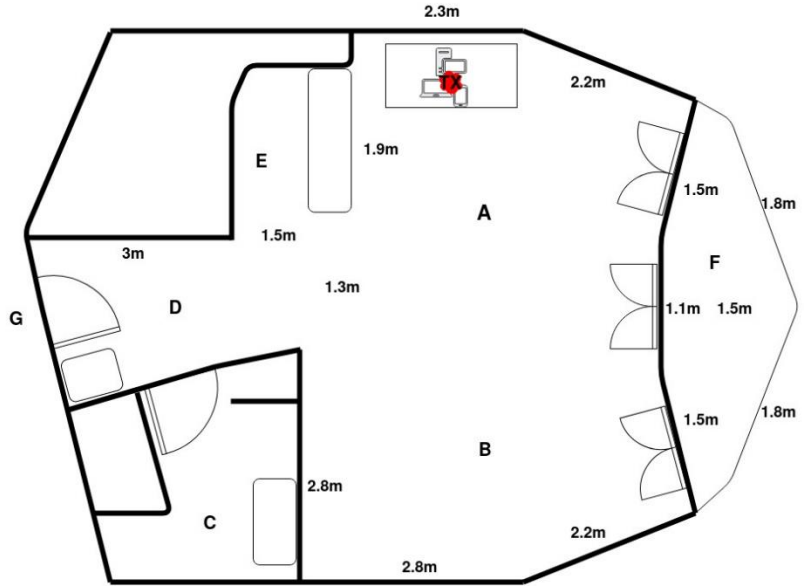
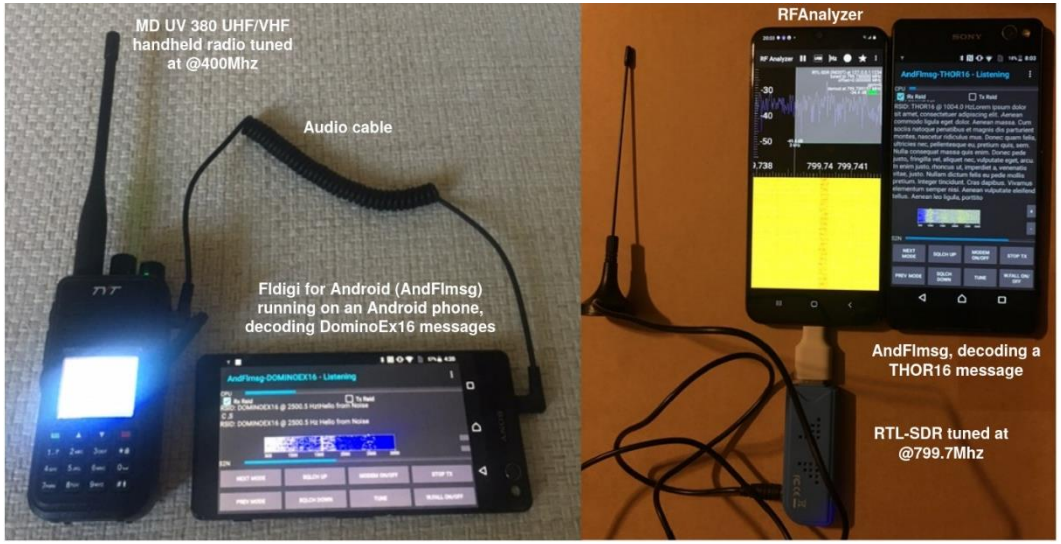
Examples of Exfiltration





E.g., robust long-range: THOR and RSIDs (e.g., MIPS32 >5m beind wall)

E.g., fast short-range: 3xPSK (e.g., MIPS32 660wpm)

E.g., flexible receivers: Handheld or SDR radio + FlDigi on smartphone

Almost zero implementation effort, not much knowledge/skills required

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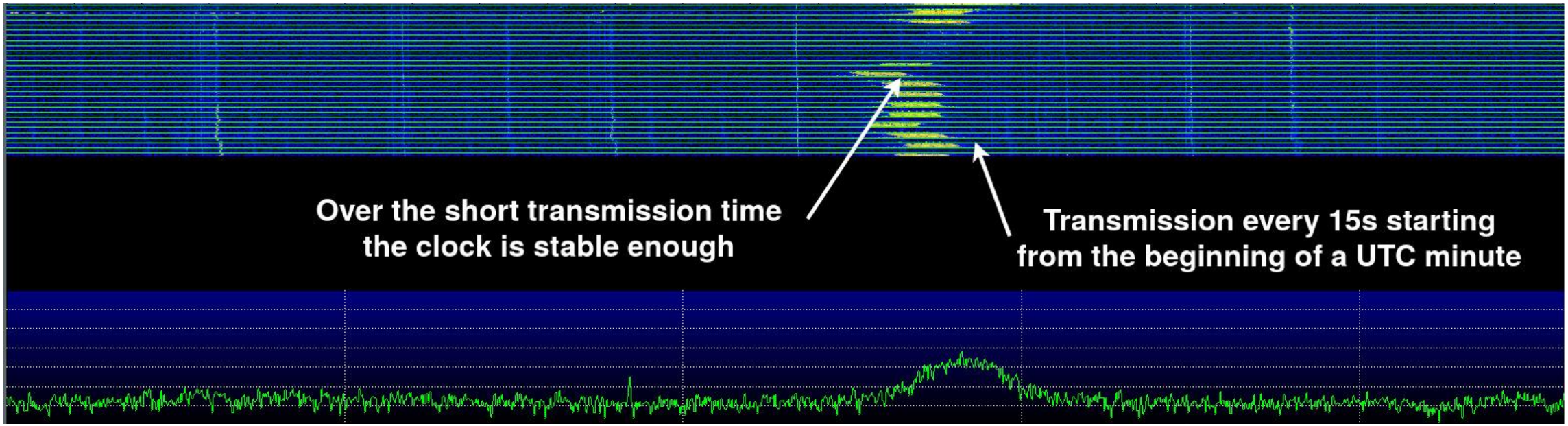
Examples of Tracking

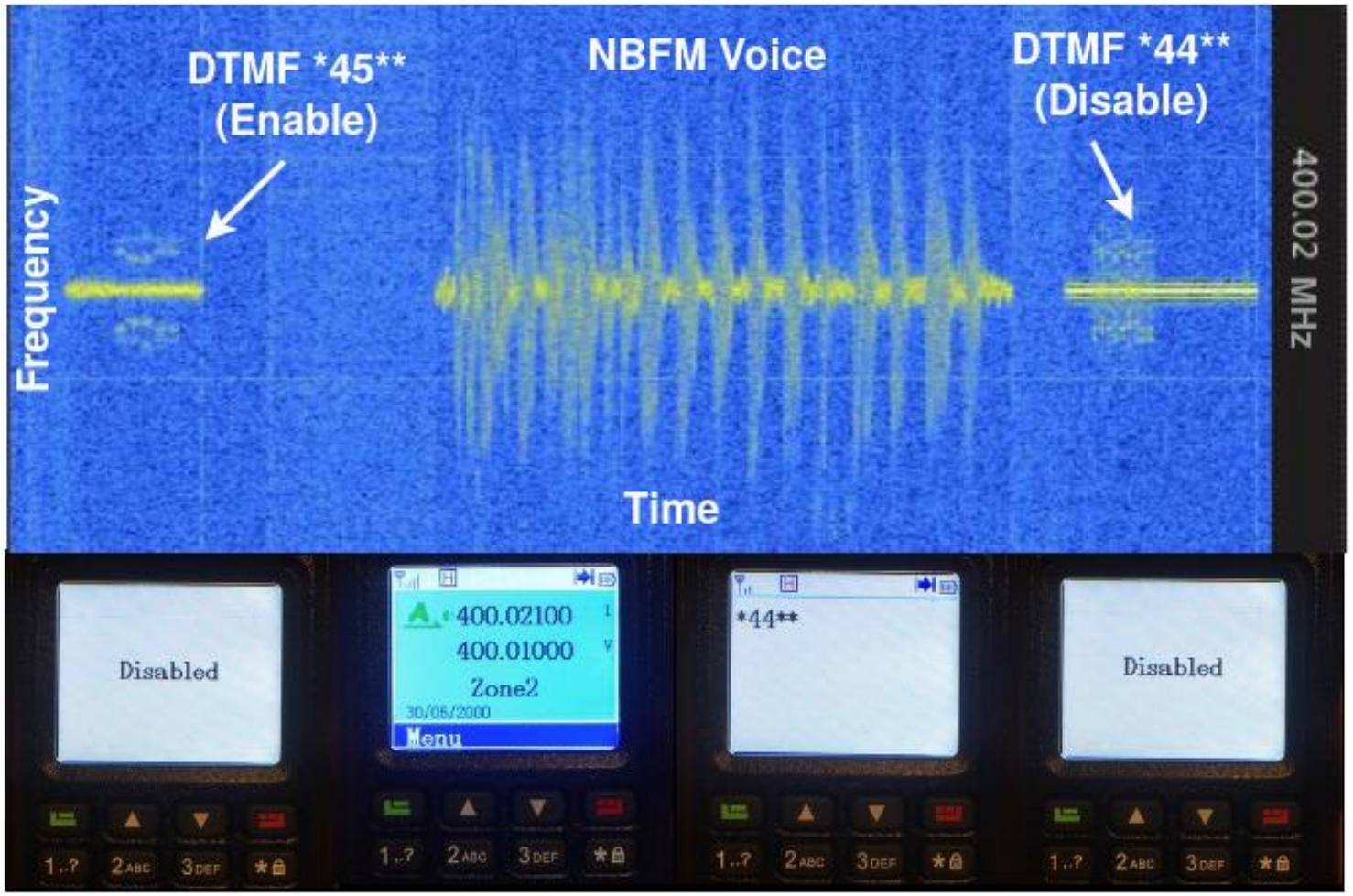


Tracking using FT4 beacons, up to 5m on Galaxy S5 Mini
Using existing reception tools

J. Taylor, FT4, https://physics.princeton.edu/pulsar/k1jt/FT4_Protocol.pdf.

J. Taylor, WSJT, https://physics.princeton.edu/pulsar/K1JT/.

Examples of Injection



IoT to UHF radio injection, a few meters

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Countermeasures

Soft-TEMPEST-specific (HW)
Reduce leakages and coupling

Soft-TEMPEST-specific (SW)
Reduce timing resolution and software control on hardware

Applications specific (SW/HW):
Shield smartphone, spoofing detection, …

Future work and conclusion

Future work

Optimizations

Time resolution, other types of one-bit coding, ...

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Time resolution, other types
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Other sources / languages
JavaScript, WebAssembly, GPU, …
(some preliminary results)

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Spoofing and jamming
Radios, sensors, on the same device
(Radio Frequency Interference) ...

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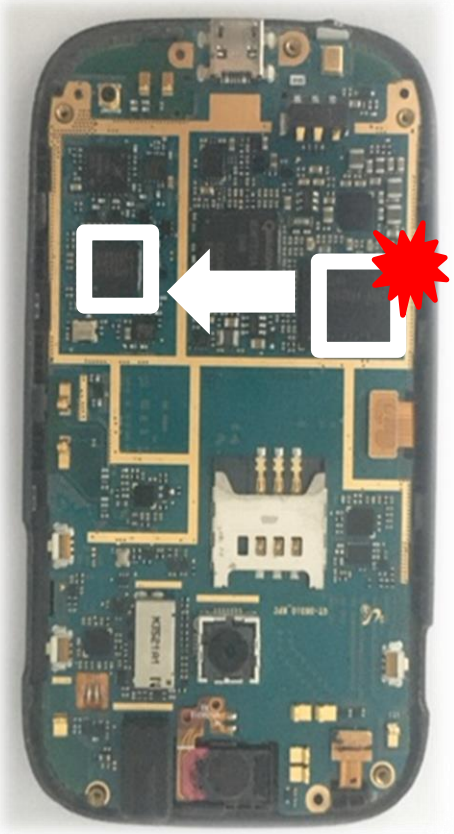
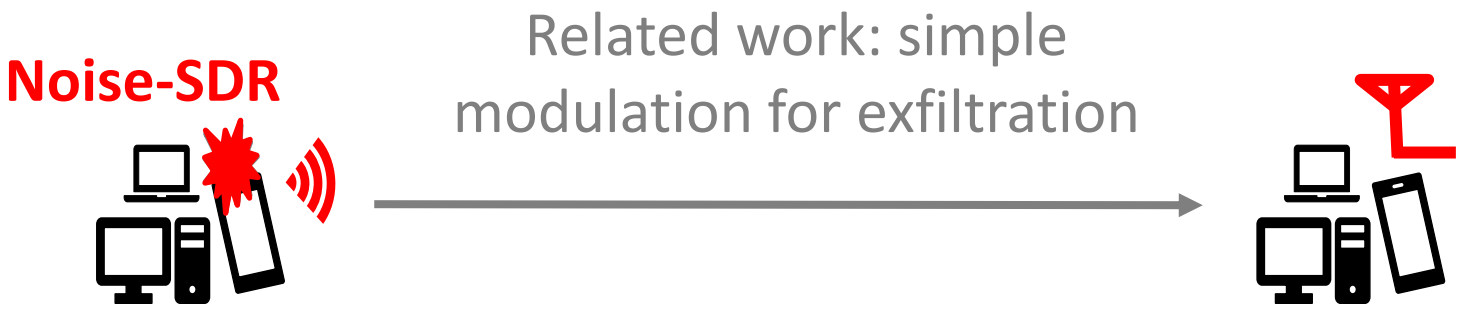


Noise-SDR
+ RF Interference

https://github.com/eurecom-s3/noise-sdr

Noise-SDR: Arbitrary Modulation of Electromagnetic Noise from Unprivileged Software and Its Impact on Emission Security



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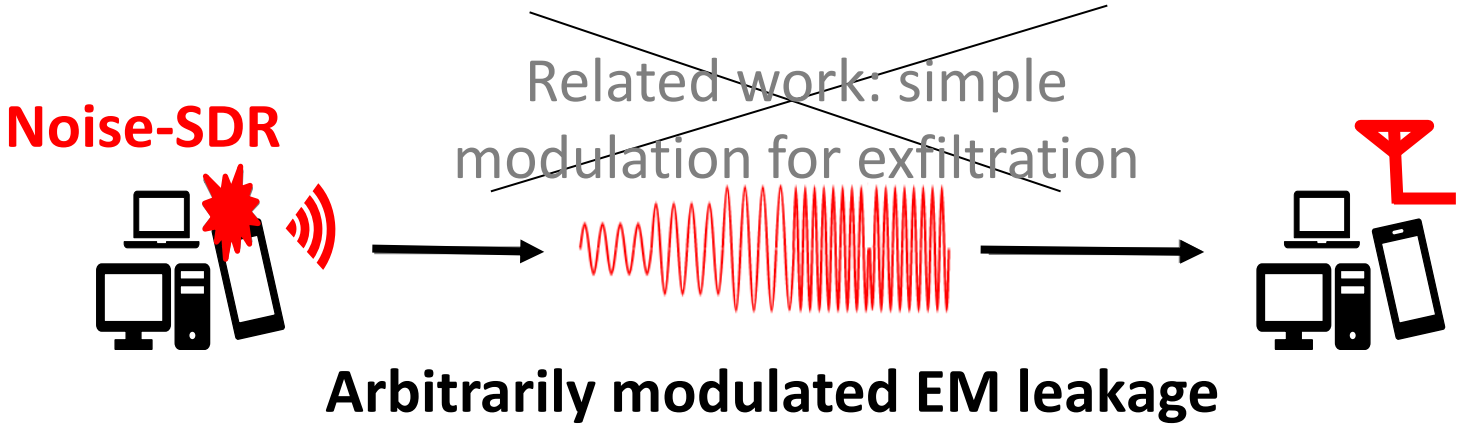

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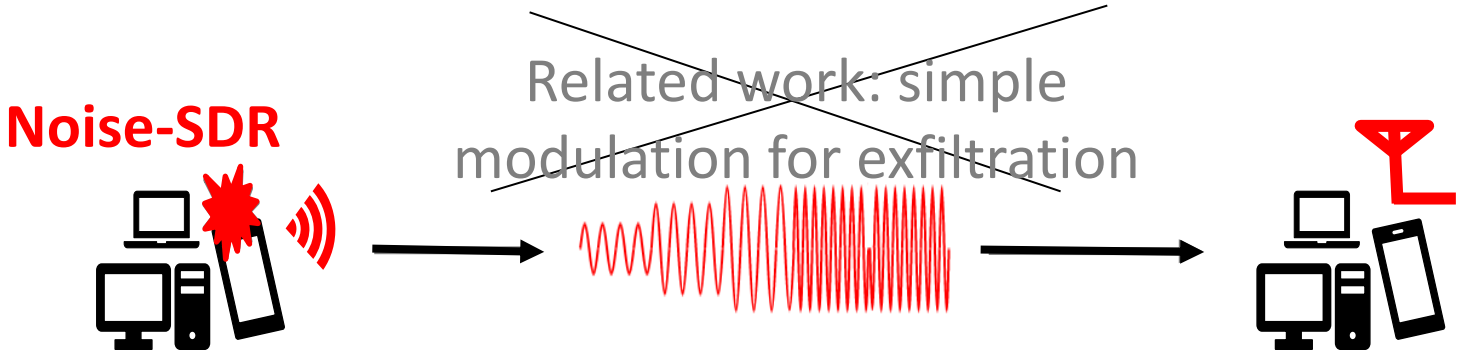

Arbitrarily modulated EM leakage

How: DRAM accesses, pass-band one-bit coding, software-defined

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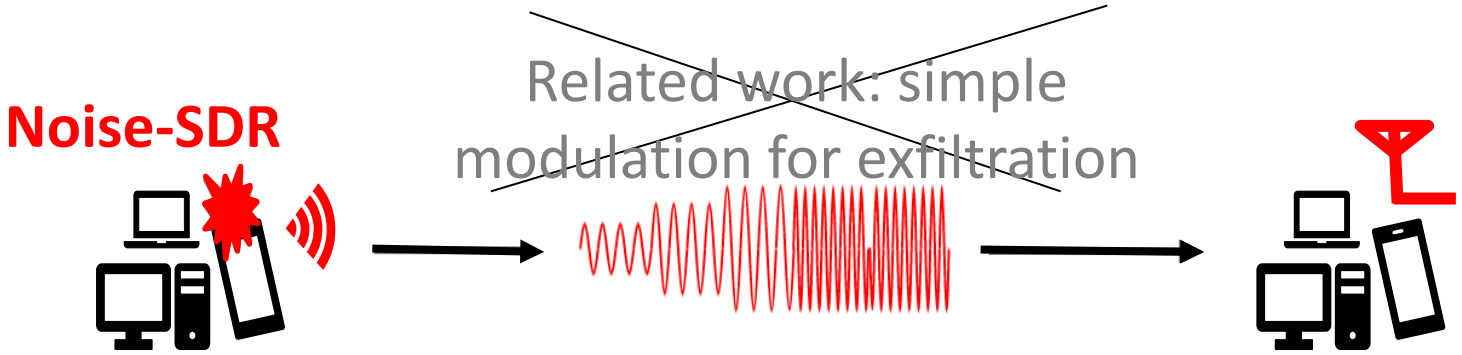

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Pros: flexibility, performance, reuse of existing protocols

Cons: limited bandwidth, center frequency

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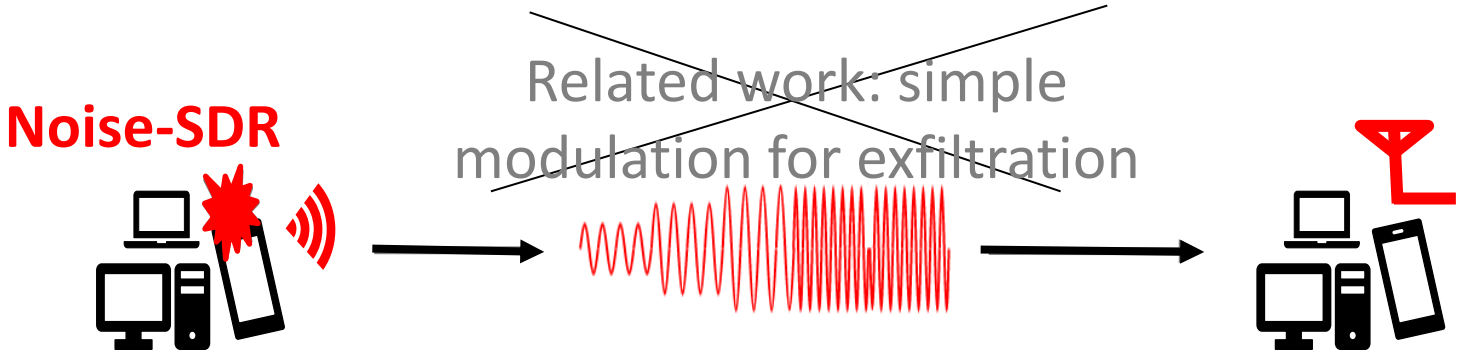

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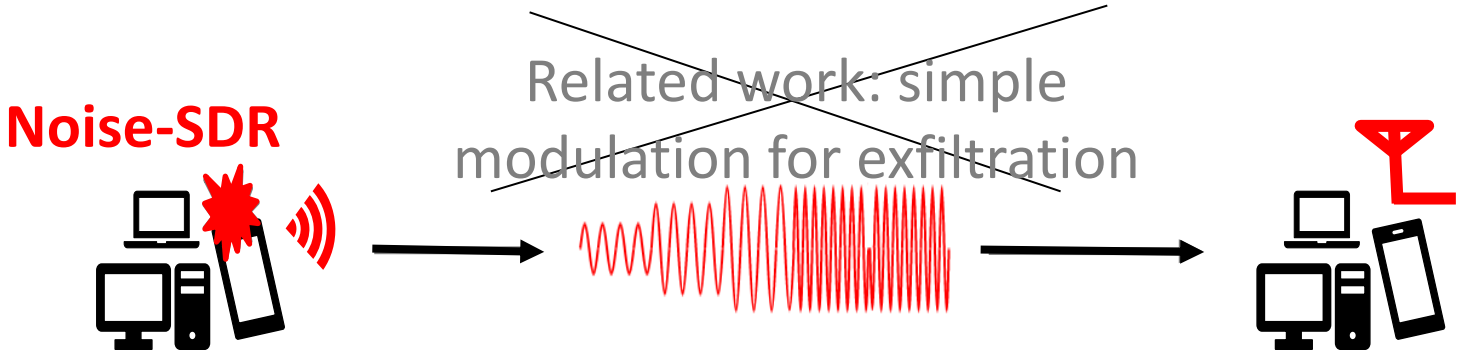

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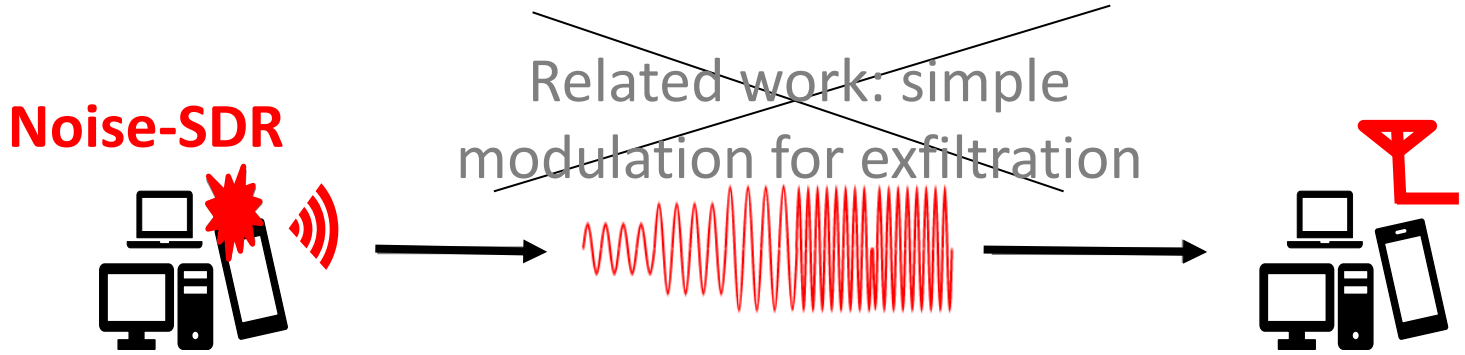

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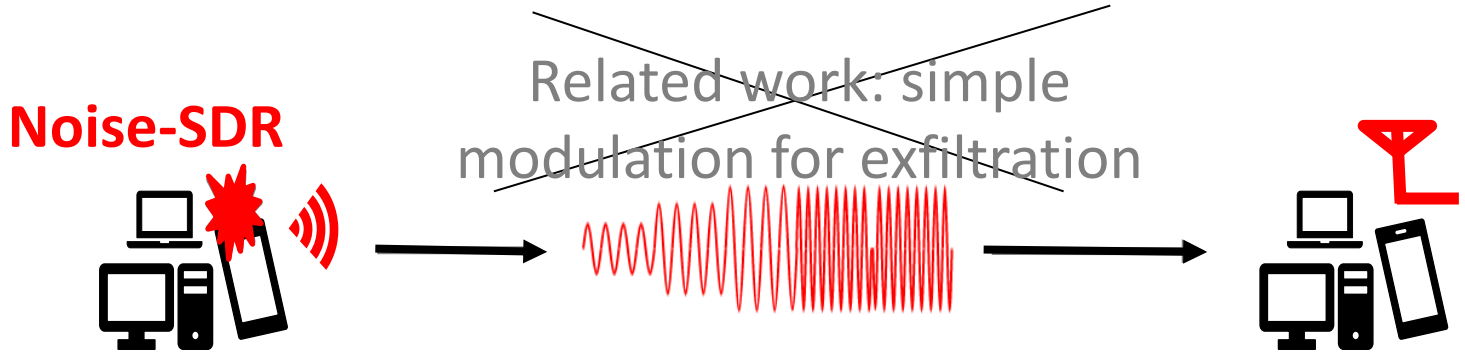
Questions?



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