Insights from Waves: Gathering Forensically-useful Insights from IoT Devices with Electromagnetic Side-Channel Analysis

DFRWS EU 2020, Oxford, UK.

UCD Forensics and Security Research Group

Outline

- Introduction (30 mins)
- GNURadio Companion Flowgraphs (45 mins)
- Software Defined Radio Programming (45 mins)
- Module Development for EMvidence Framework (45 mins)

Introduction (30 mins)

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Digital Forensics

- Acquiring data from computing devices that can help to progress investigations.
- Increasing usage of computing devices adding up to more forensic data sources.
- More and more computing devices are employing encryption to store data.
- Most digital forensic literature assumes either that,
  - Cryptography is not employed
  - Cryptography is bypassed somehow as a part of the legal process.
- It is not possible to ignore the threat posed by encrypted devices.

Forensics of Internet of Things

- IoT opens up new evidence sources from unexpected places.

  ...health implants, sports wearables, smart burglar alarms, smart thermostats...

- Highly heterogeneous device designs.

- Application of encryption worsen the usability of IoT in forensics.

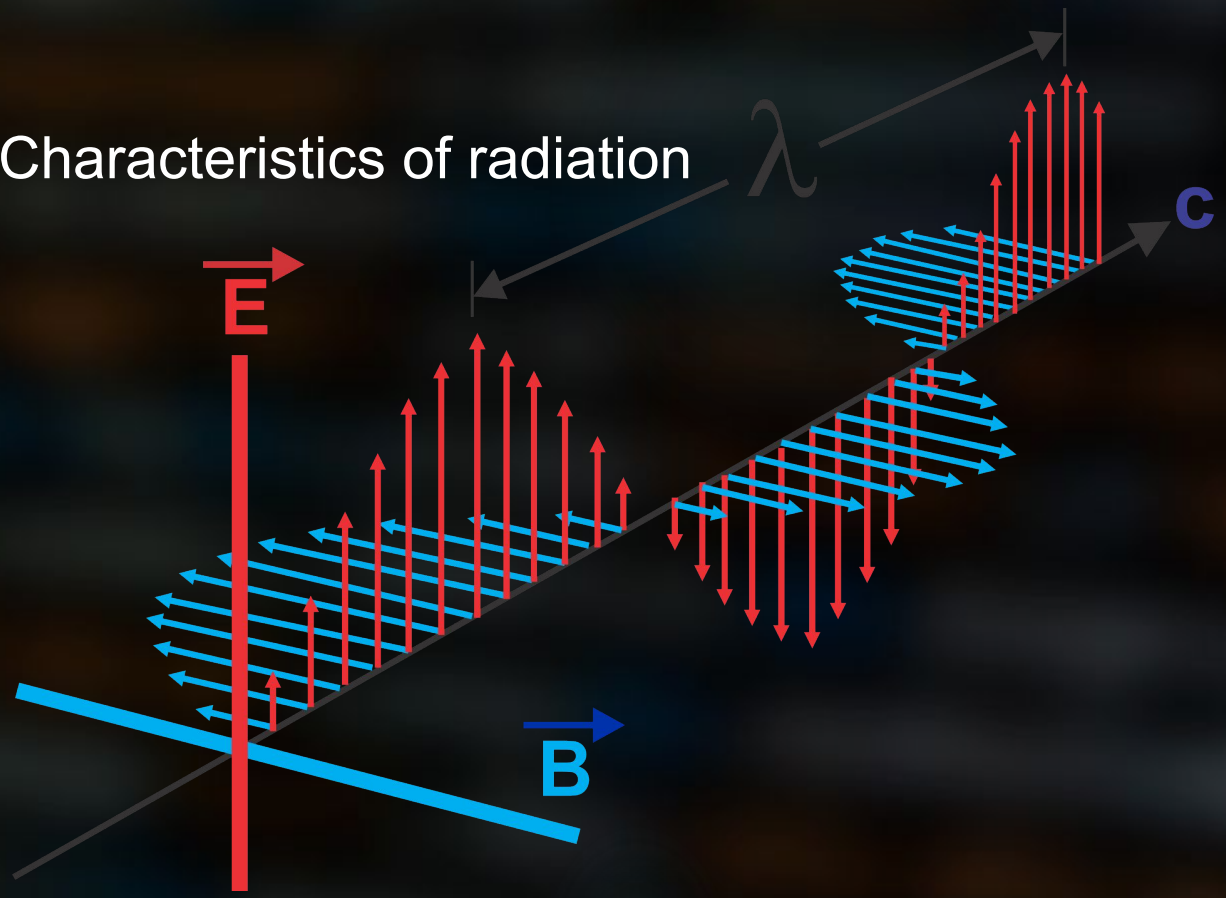
Electromagnetic Side-Channel Analysis

Time-varying electrical currents ⇒ Electromagnetic radiation

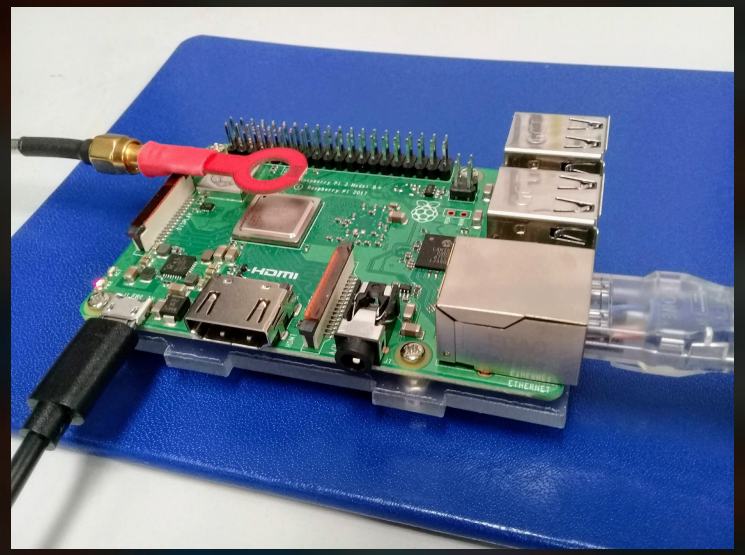
Nature of the time-varying current ⇐ Characteristics of radiation

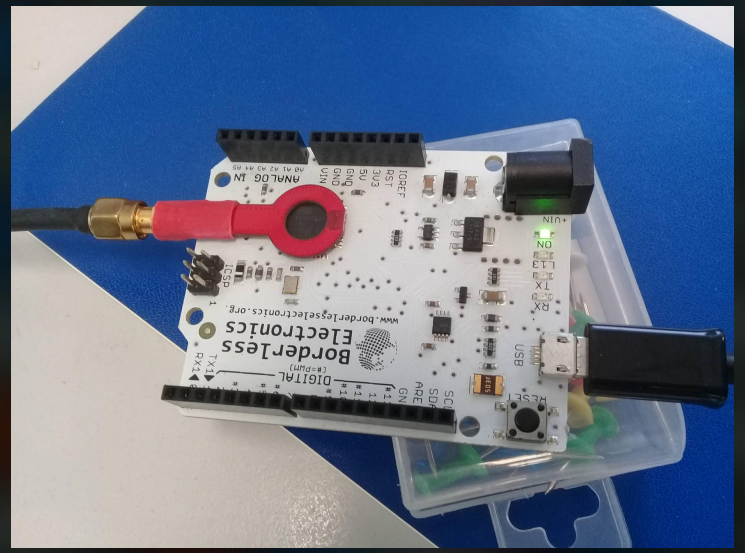
EM radiation from computer processors leak information

EM side-channel analysis (EM-SCA)

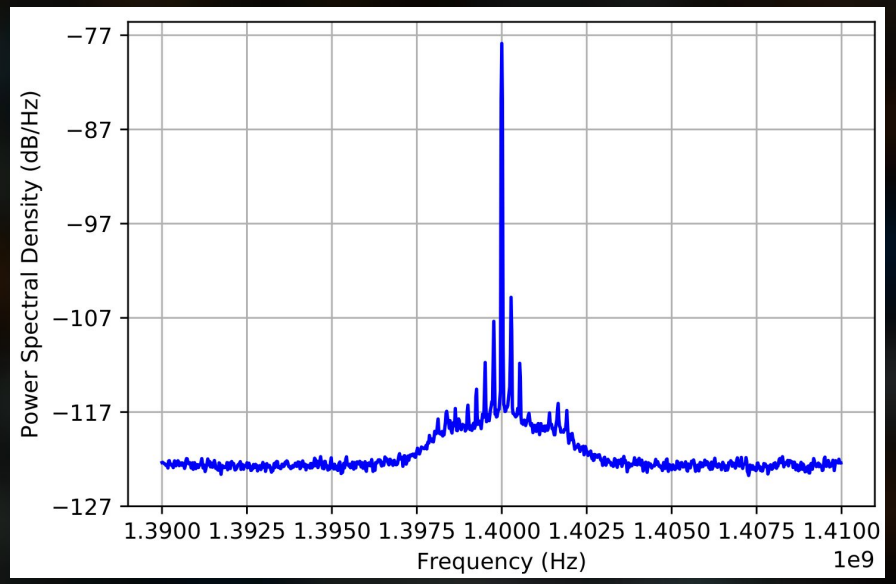


Observation of EM Side-channel





- CPU clock/oscillator is the main source of EM noise.
- EM emissions can be observed at clock frequency and its harmonics.
- Signal attenuates rapidly with distance from the CPU.
- H-loop antennas placed closer to the CPU can pick up strong signals.
- When the fundamental frequency is noisy due to external sources, harmonics can be used.



Electromagnetic Side-Channel Analysis

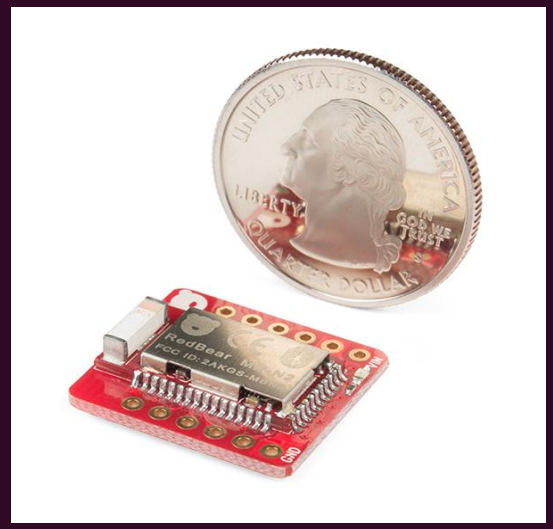
- EM-SCA has been applied to recover cryptographic keys,

  e.g., Camurati et al. (2018)
- Target device: BLE-Nano running AES-128 encryptions.
- ~ 8000 EM trace samples.
- Correlation electromagnetic

  analysis (CEMA)
- 18 minutes to recover the key

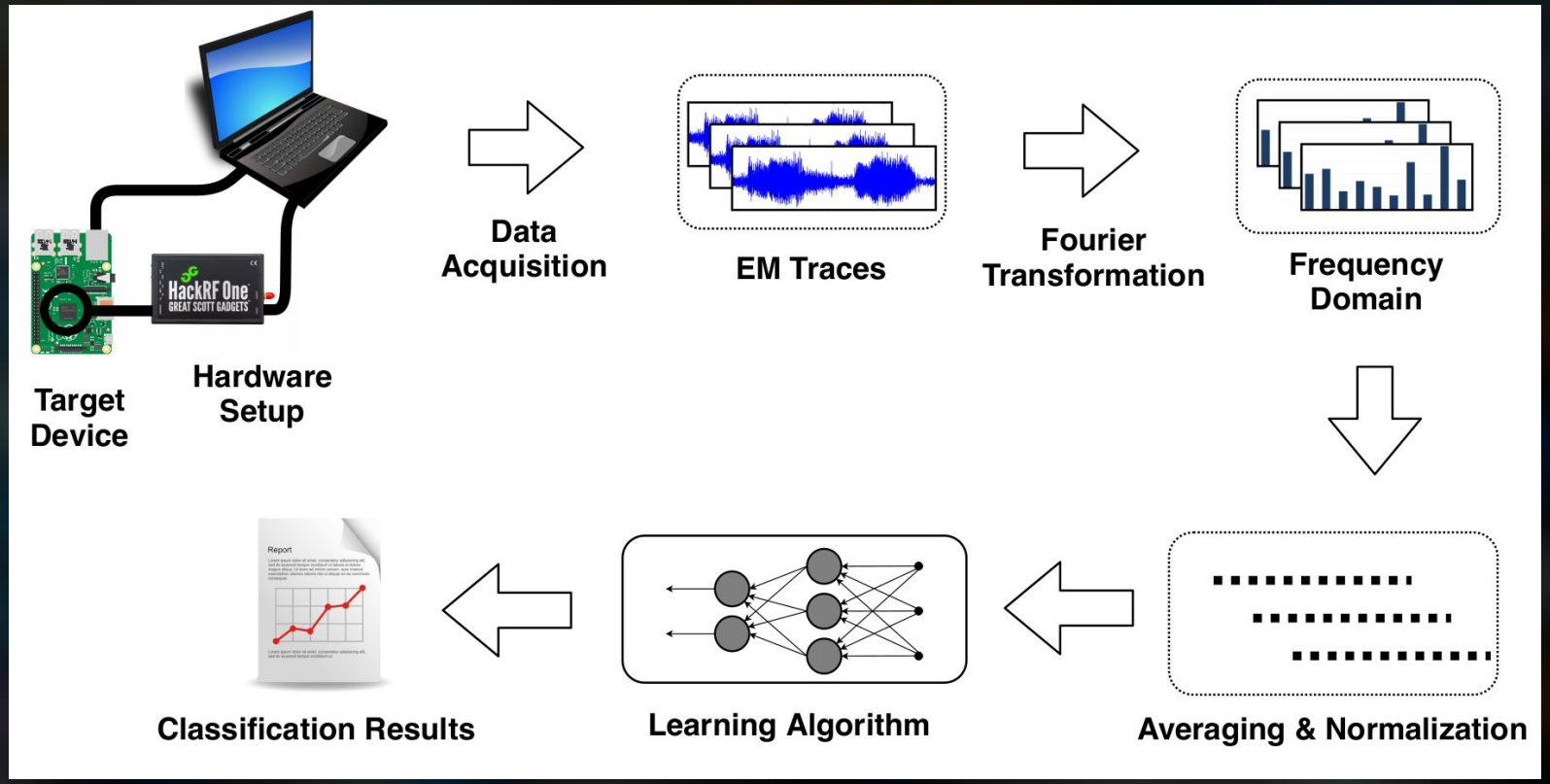
Current EM-SCA assumes that the attacker has physical access to the device to make any tampering.
In forensics, we don't!

```
Subkey 15, hyp = ed:  0.012530354407226786
Subkey 15, hyp = ee:  0.017266581888572823
Subkey 15, hyp = ef:  0.010556395126552152
Subkey 15, hyp = f0:  0.02396490987572155
Subkey 15, hyp = f1:  0.012949217484922705
Subkey 15, hyp = f2:  0.014502574032304778
Subkey 15, hyp = f3:  0.014963314285949247
Subkey 15, hyp = f4:  0.012954752080796888
Subkey 15, hyp = f5:  0.0130315561783500 3
Subkey 15, hyp = f6:  0.013772034631913068
Subkey 15, hyp = f7:  0.019364248397445407
Subkey 15, hyp = f8:  0.010932180008903168
Subkey 15, hyp = f9:  0.013027691526298332
Subkey 15, hyp = fa:  0.01665869128411864
Subkey 15, hyp = fb:  0.015427833690631214
Subkey 15, hyp = fc:  0.011935004419024819
Subkey 15, hyp = fd:  0.014665594979696694
Subkey 15, hyp = fe:  0.018540794601137632
Subkey 15, hyp = ff:  0.018274501184871804
Best Key Guess:   56   89   ed   be   4c   65   db   f2   aa   2c   bd   c9   26   42   e6   e1
Known Key:        56   89   ed   be   4c   65   db   f2   aa   2c   bd   c9   26   42   e6   e1
PGE:             000  000  000  000  000  000  000  000  000  000  000  000  000  000  000  000
SUCCESS:           1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
NUMBER OF CORRECT BYTES: 16
```

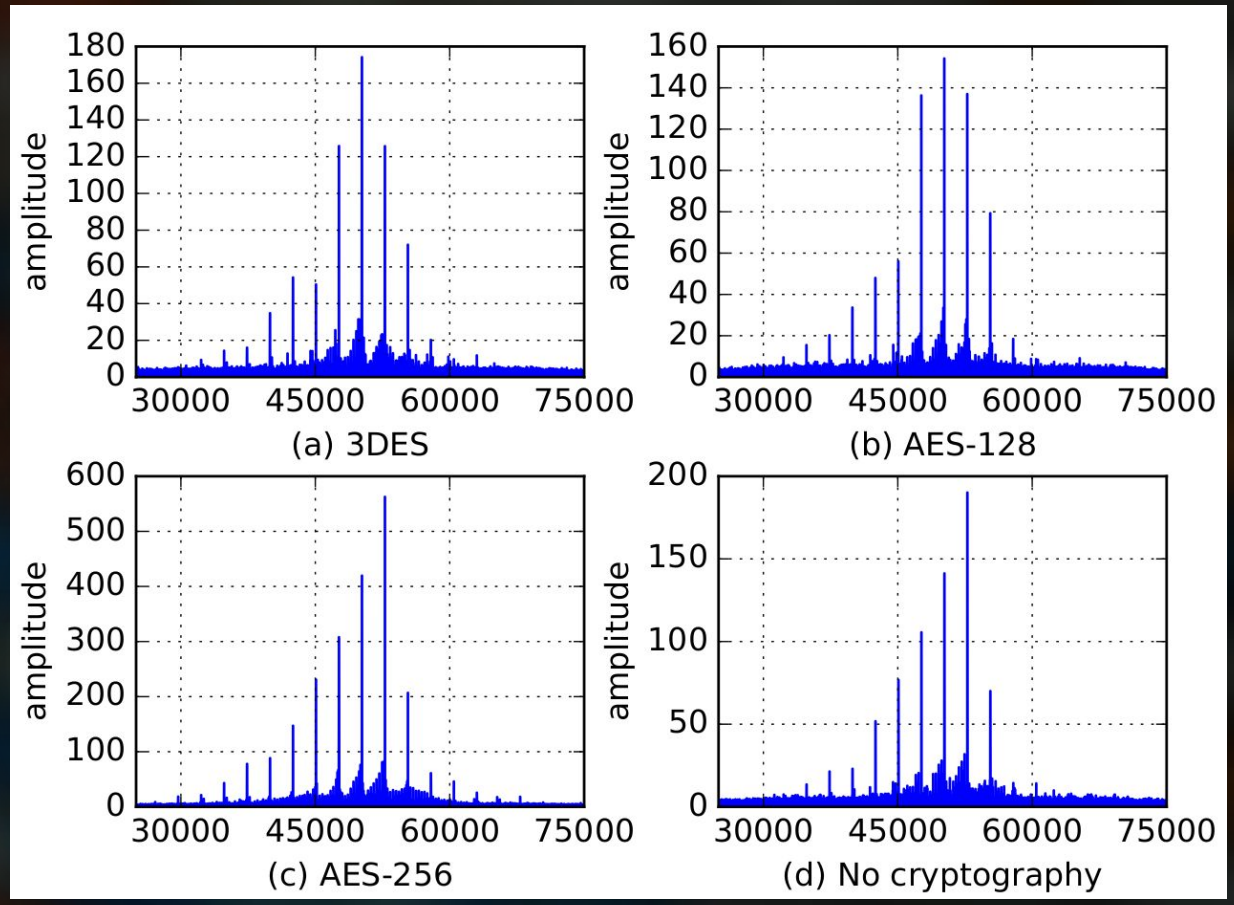


Some Experimental Results

1. Discriminating cryptographic activities
2. Detection of software behaviour
3. Detecting modifications to firmware



Discriminating Cryptographic Activities



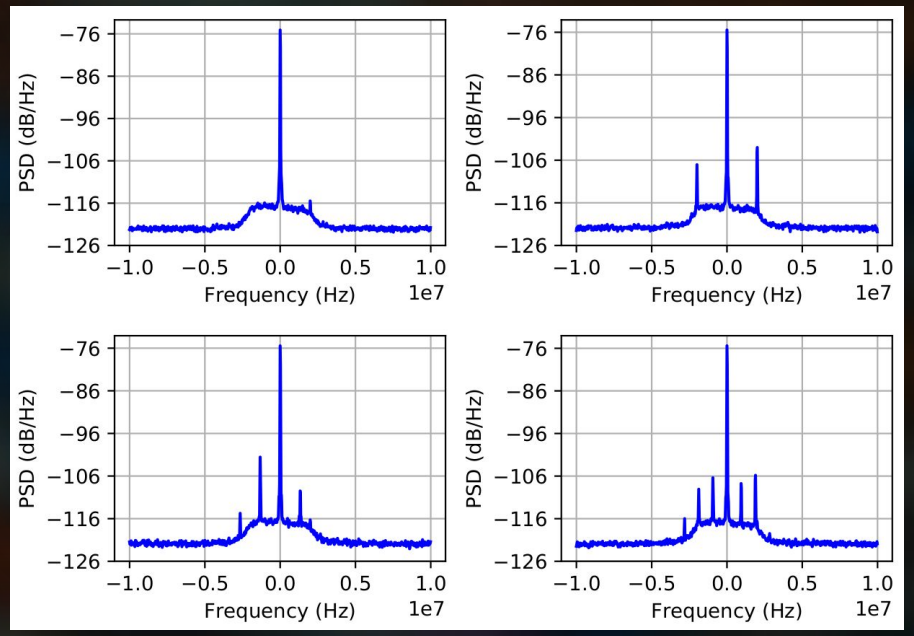
- Raspberry Pi as the target device.
- Three cryptographic classes and a ``no cryptography" class.
- From FFT to 500 features by averaging.
- 4 layer NN (2 hidden - 10x5)
- 600 samples per class.

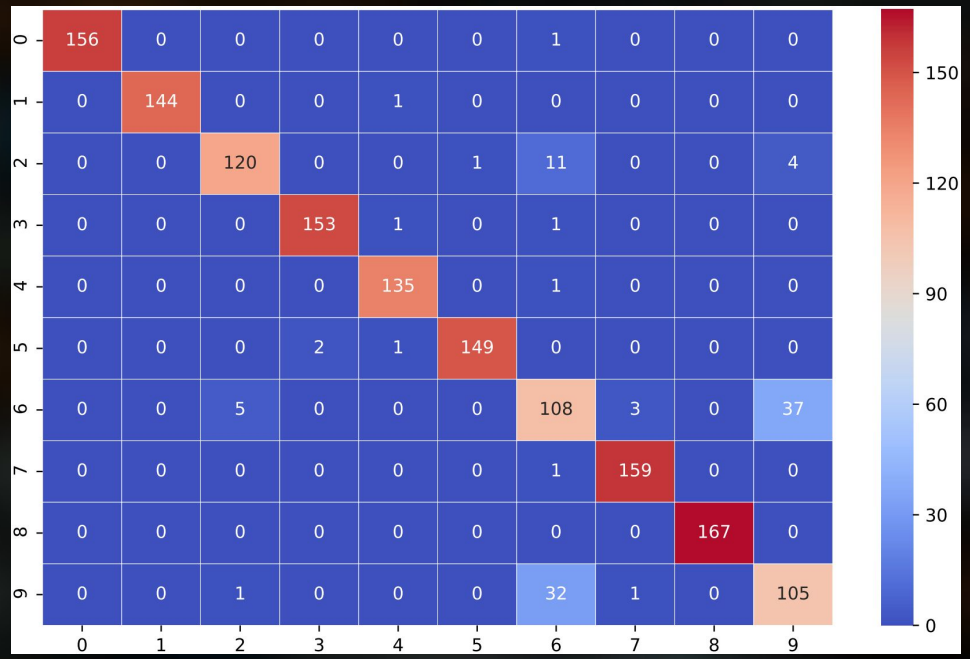
Activity	Precision	Recall	F1-Score
Other	0.93	0.85	0.89
AES-256	0.78	0.86	0.82
AES-128	0.99	0.92	0.95
3DES	0.81	0.85	0.83

Detection of Software Behaviour


```
/* Arduino test program */
void setup(){
}
void loop(){
    for(int i=0, i<20, i++) { delay(10); }
    for(int i=0, i<20, i++) { delay(10); }
    /* further loops */
}
```

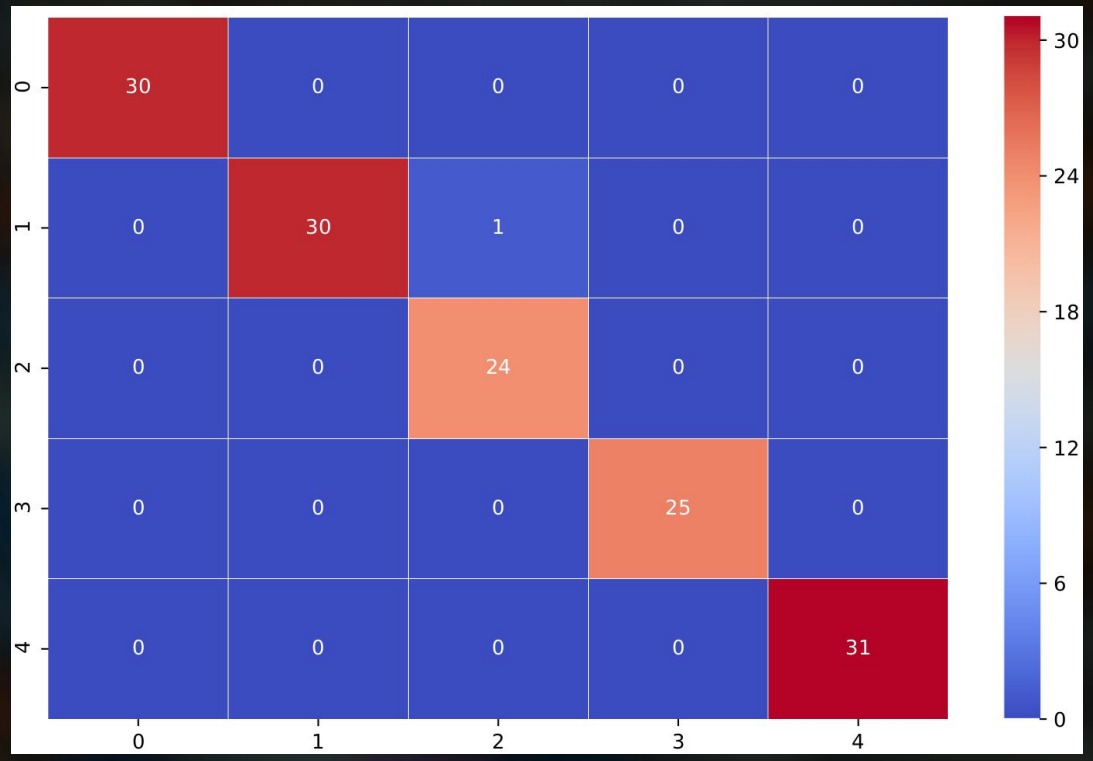
- Arduino Leonardo running 10 programs
- FFT (20,000,000) to a vector of 1000 features.
- 1000 buckets with max values.
- Over 90% classification accuracy

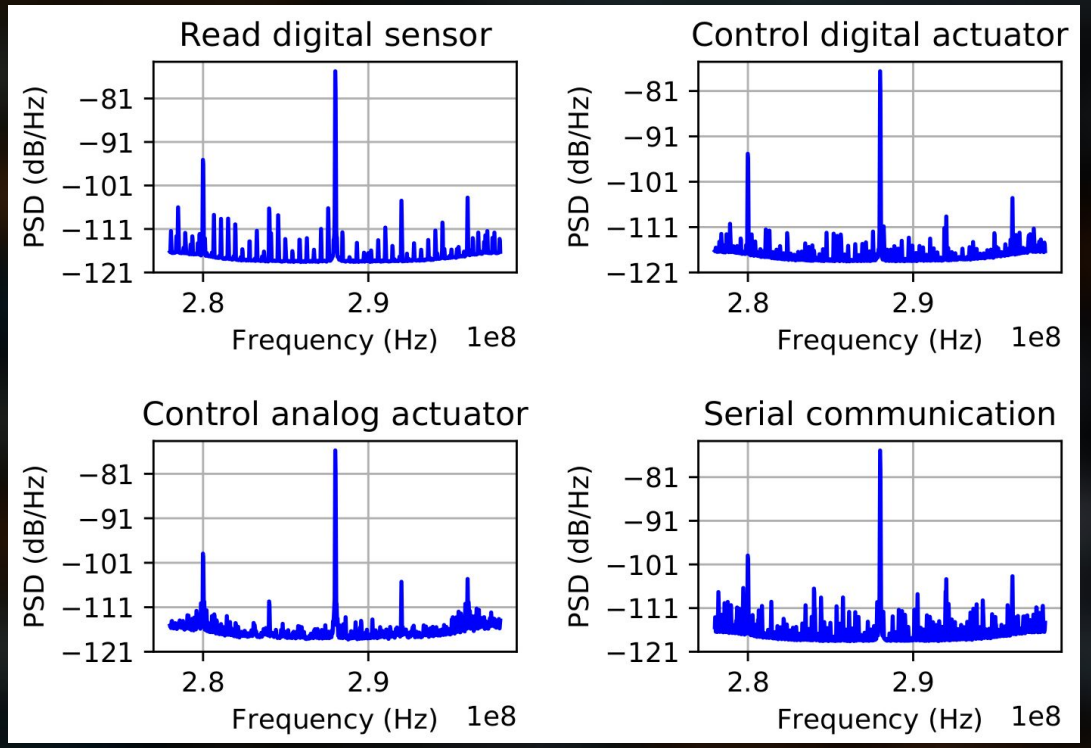




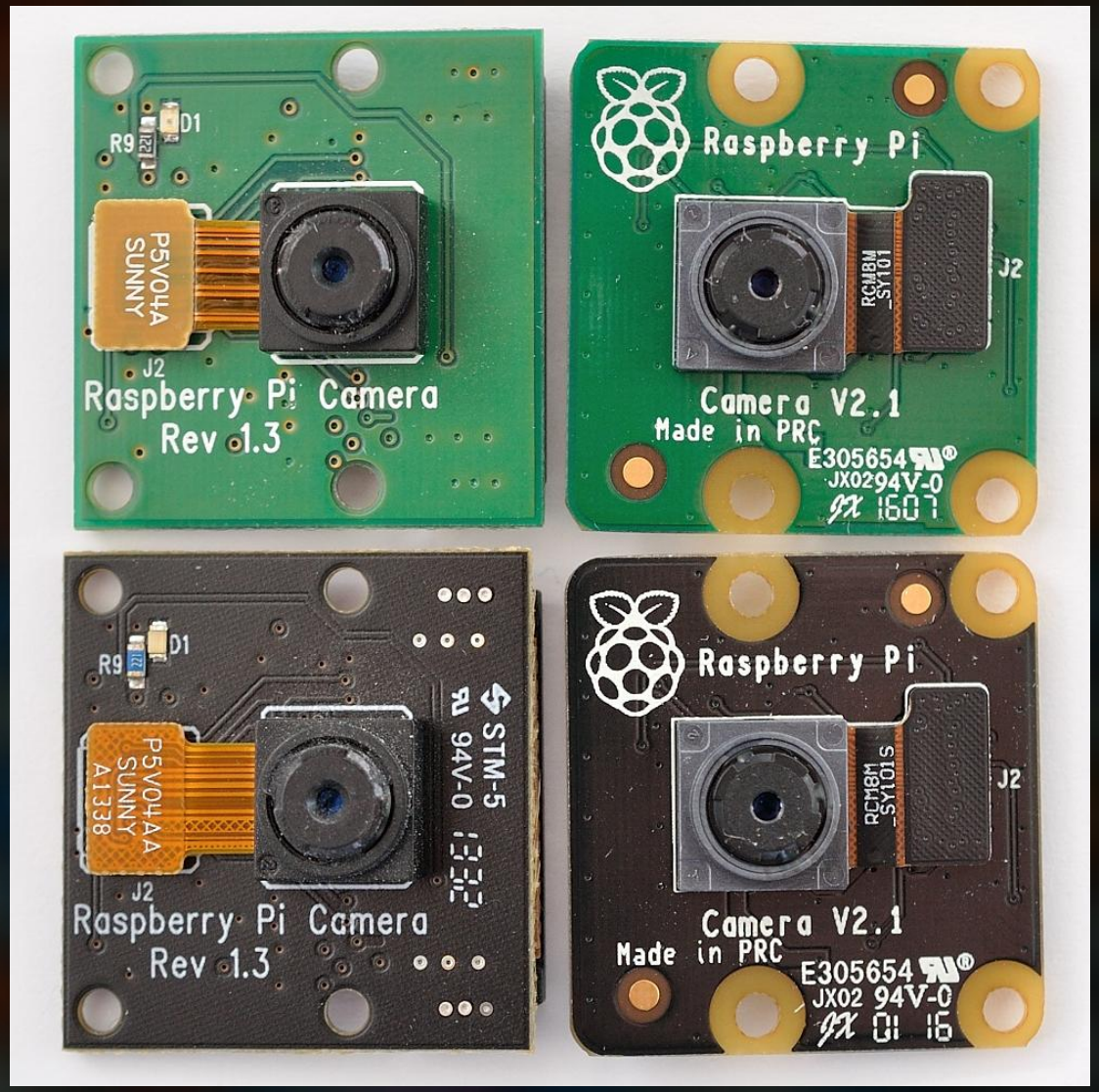
Detection of Software Behaviour (cont.)

- An IoT device with 5 internal states emulated using an Arduino.
- Similar neural network classifier like the previous case.
- Detection accuracy of over 99%





Detecting Modifications to Firmware



- Arduino Leonardo as the target device.
- FFT to 1000 features using max values.
- One-class SVM with a non-linear kernel (RBF).
- 1 legitimate program and 20 slightly modified programs for testing.
- 100% detection accuracy for all the tested programs.

What we've learned so far...

- We can identify known behaviors of software running on IoT devices.
- We can identify when known cryptographic algorithm implementations are running on an IoT device.
- Such insights can help inspecting an IoT device in a forensic investigative scenario.

- Ongoing work:

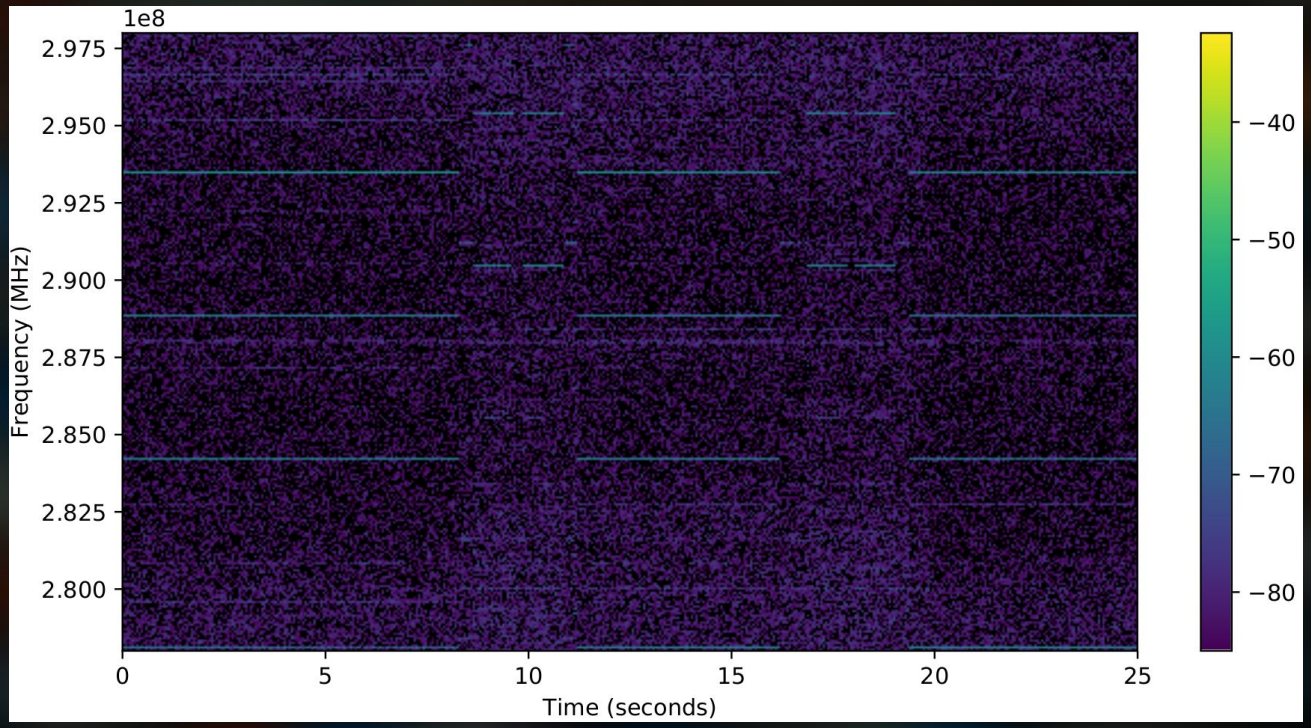
Cryptographic key retrieval on a forensic setting.

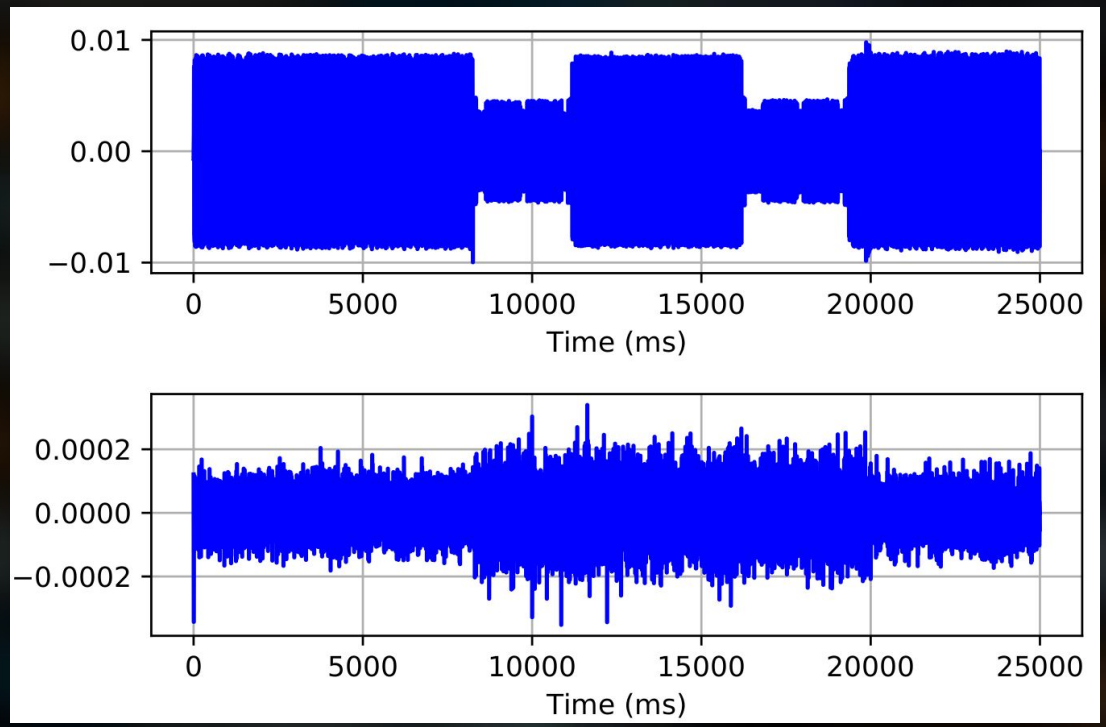
Cryptographic Key Retrieval on a Forensic Setting

- A key retrieval algorithm such as CEMA requires,
  a. a large number of EM trace files.
  b. each trace file to be enclosing a unique encryption/decryption operation using the same key.
  c. all the trace files to be precisely aligned, i.e., same time step in every trace should represent the same CPU activity.
- Currently, all these are achieved by instrumenting the target device in software or hardware means during data acquisition.
- When attacking a device in a digital forensic investigation, such tampering are not acceptable.

Cryptographic Key Retrieval on a Forensic Setting (cont.)

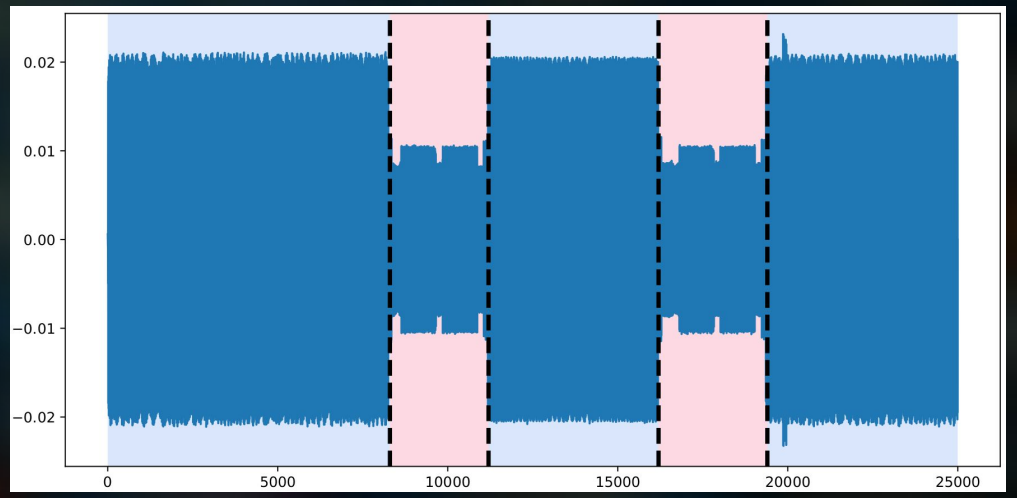
- Here's how signal looks like when running ECC encryption twice.
- Some channels clearly give away the starting and ending positions of encryption.

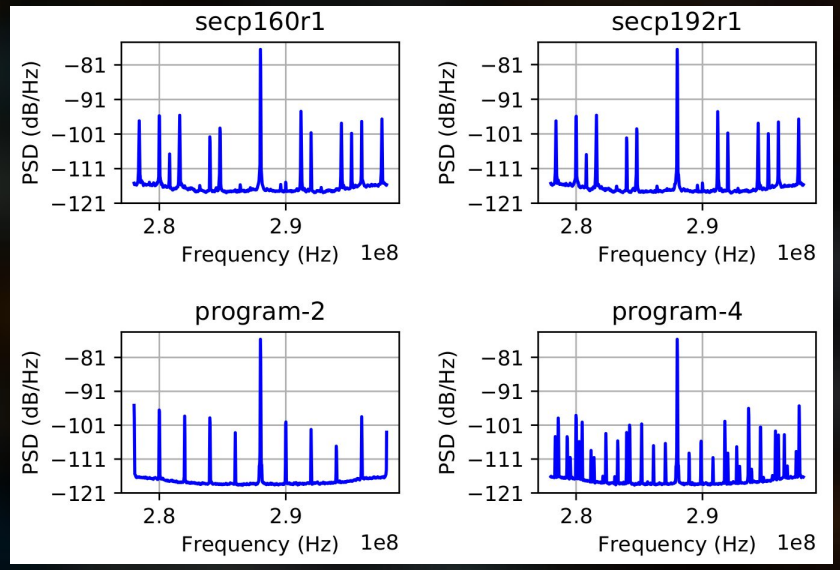




Cryptographic Key Retrieval on a Forensic Setting (cont.)

- A change-point detection algorithm, i.e., PELT, is used to segment the original signal into pieces.
- Cryptography-related pieces are identified using a classifier.
- However, key retrieval algorithm still doesn't work with such traces.
- Use of extremely small sliding windows is currently being explored.

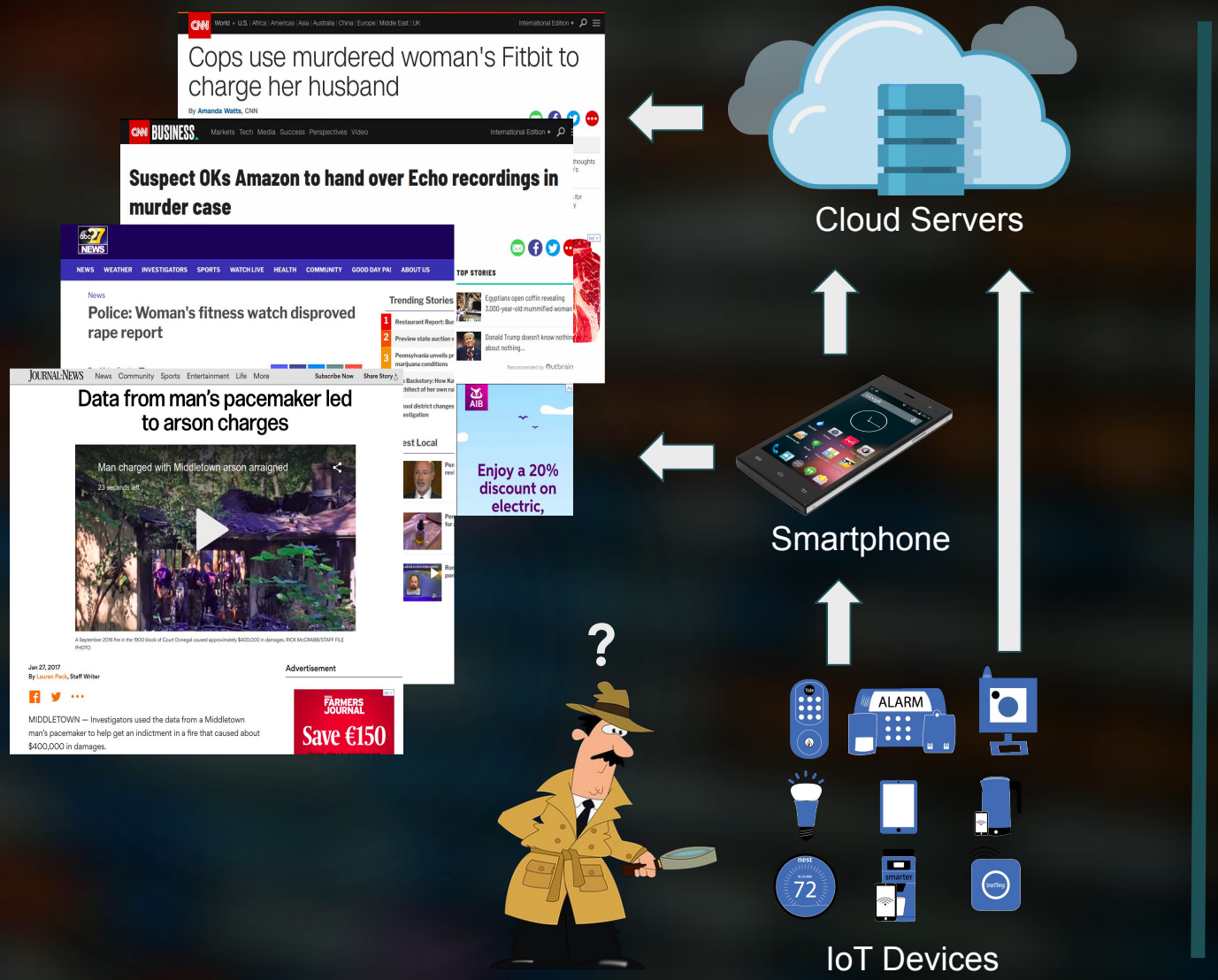




Limitations

- EM-SCA only applicable if the device is giving out sufficient EM radiation.
- Properly shielded devices are difficult to reach without high powered signal amplifiers.
- A firmware update can change the EM signature completely.
- Key recovery requires large number of traces.
  a. encryption should occur frequently
  b. need a sufficient time to observe as many encryption as possible
- Presence of multiple devices within the vicinity that produce EM radiation in similar frequencies can make the isolation of one device difficult.
- A huge variety of manufacturers/configurations for the same device - e.g., Amazon Echo.

Application of EM-SCA



- Smartphone apps and cloud servers are the window to most IoT devices.
- IoT devices are mostly black boxes due to,
  a. lack of standard forensic data gathering interfaces
  b. high heterogeneity of devices
  c. employment of encryption
- EM-SCA opens up a window to gather insights directly from the IoT devices.

Application of EM-SCA

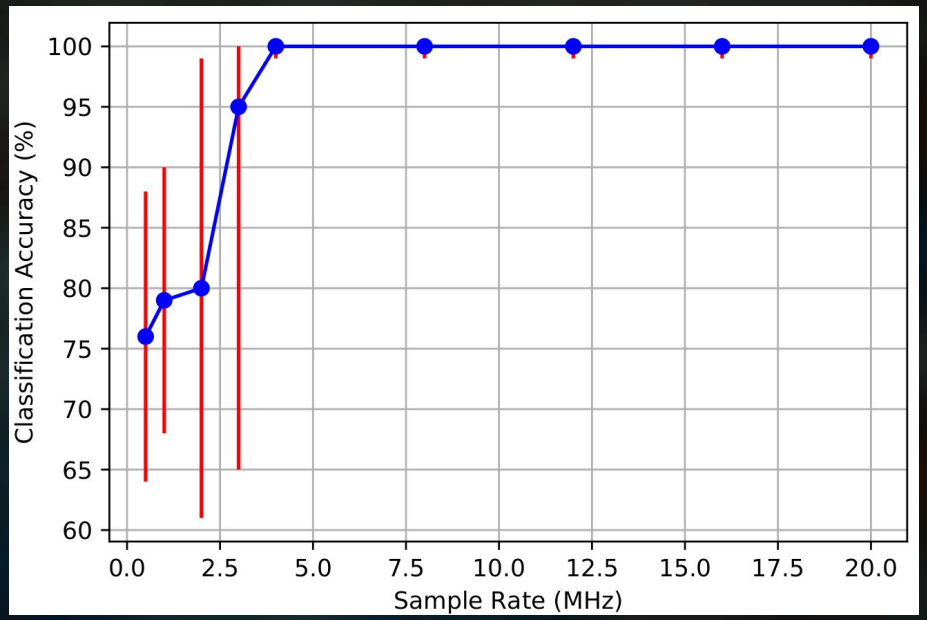
- An IP camera that takes photos when a motion is detected.
- Images are stored locally on an SD card with encryption.
- User can remotely initiate a video streaming which uses encryption as well.
- Cryptographic key is securely stored on the camera in a way not easily accessible to third parties.

How can I extract and decrypt a particular encrypted image on the SD card?

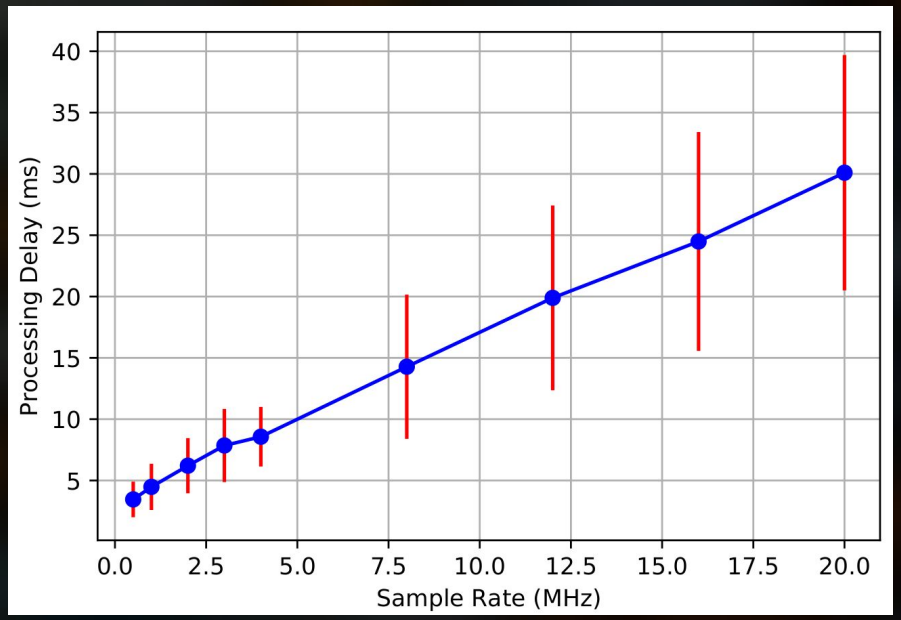
Storage and Real-time Requirements

- Each I-Q sample = 8 bytes
- Highest sampling rate = 20 MHz
- Size of the 1 minute signal capture ≈ 9 GB

  (8 bytes × 20 MHz × 60 seconds = 8.94 GB).



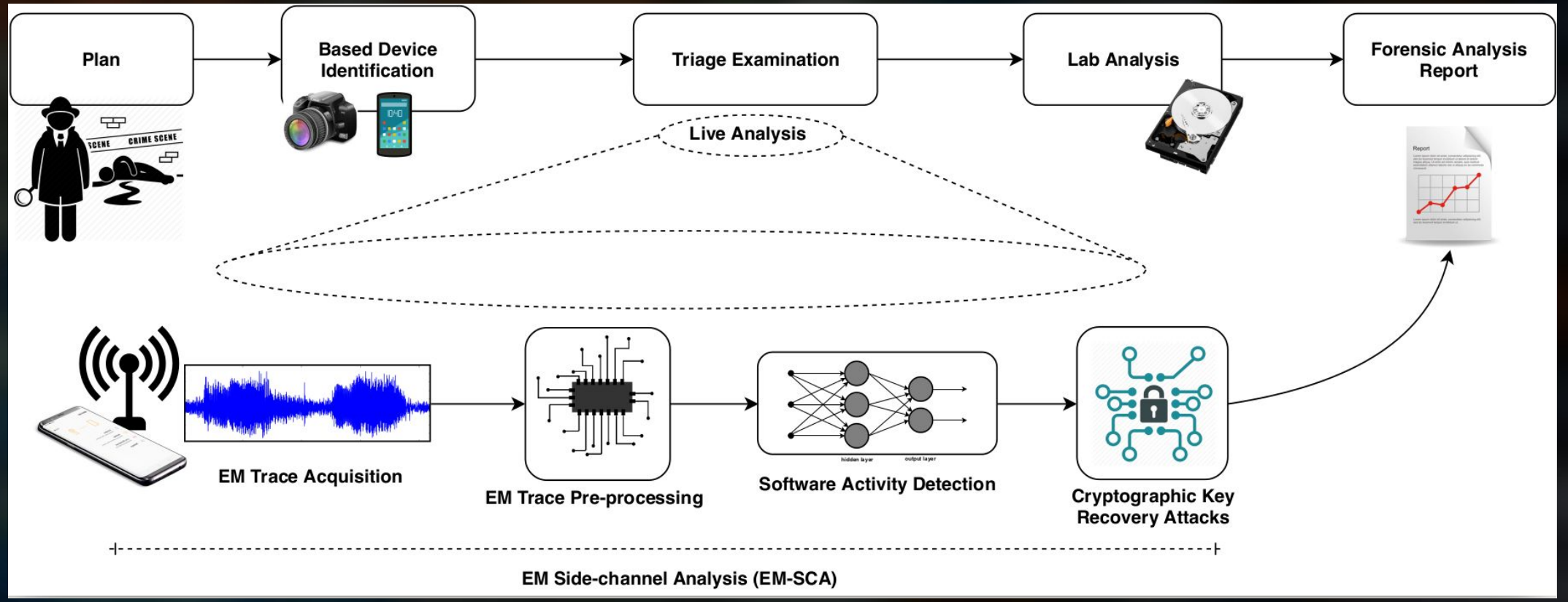
It's OK to have lower sampling rates to cope with storage requirements.



Even the highest sample rate does not exceed our capability to process data in real-time

Hence, live forensic analysis is possible!

Application of EM-SCA



Hardware for EM-SCA

Oscilloscopes / spectrum analyzers / traditional radio receivers

Difficult to handle in in digital forensic investigation settings.

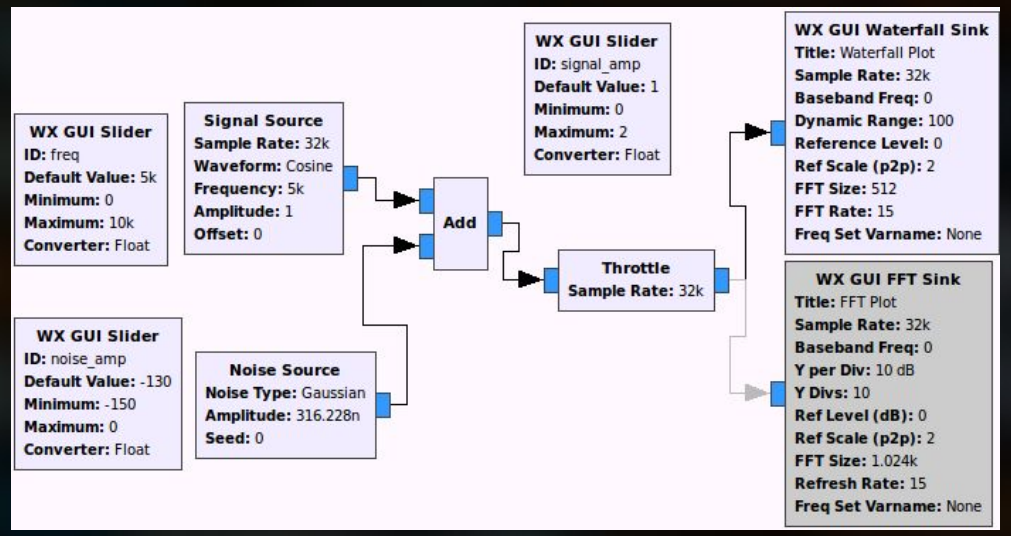
Software-defined radios (SDR)

Easily configurable with software.

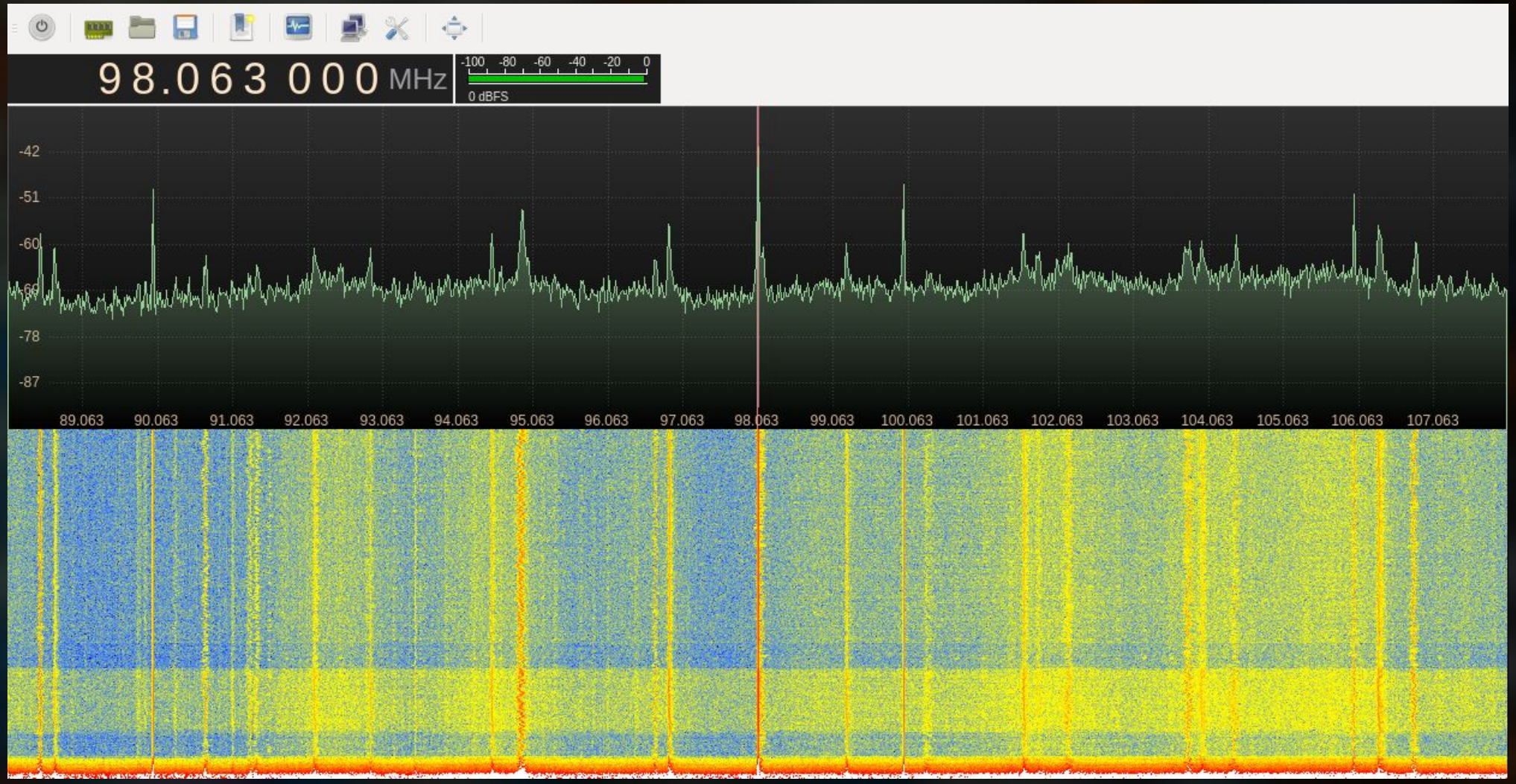
Software Defined Radio (SDR)

- A fast analog-to-digital converter (ADC).
- RTL-SDR, HackRF, USRP
- Generates digitized samples in Inphase-Quadrature (I-Q) format.
- Open source libraries to process streams of I-Q data samples.
- Can program for a task using Python or using a visual flowgraph editor, GRC.

GNU Radio
THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM



A walkthrough the spectrum with GQRX



GNURadio Companion Flowgraphs (45 mins)

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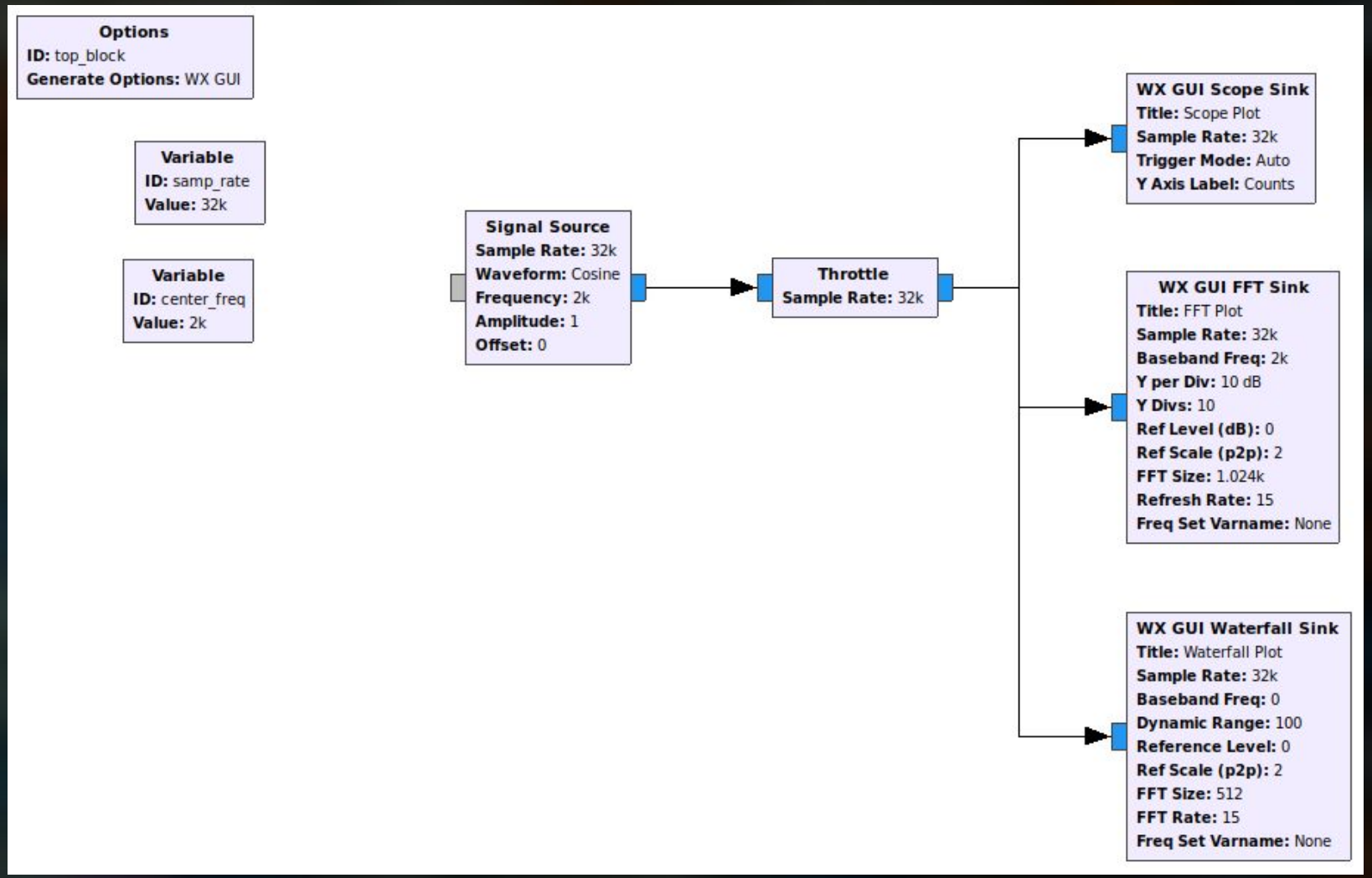
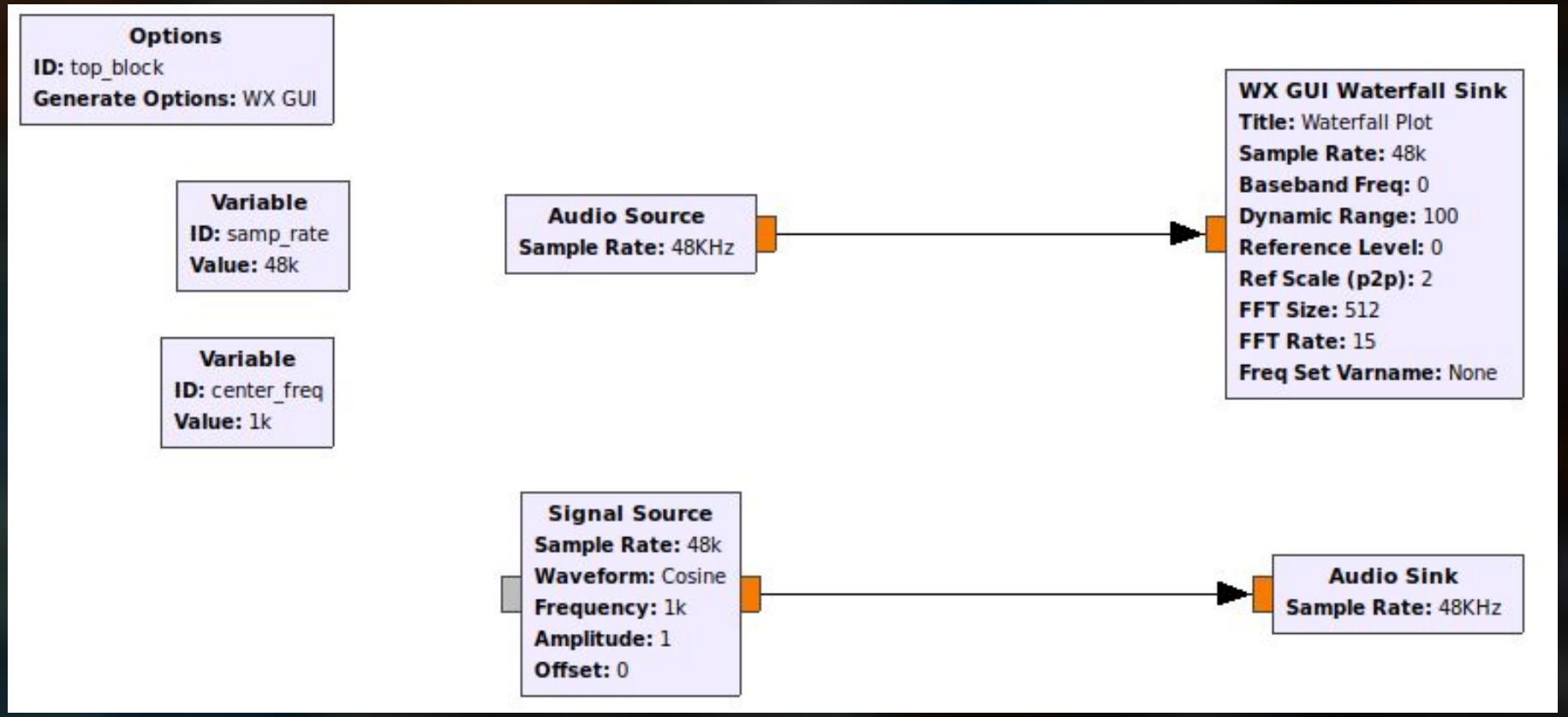
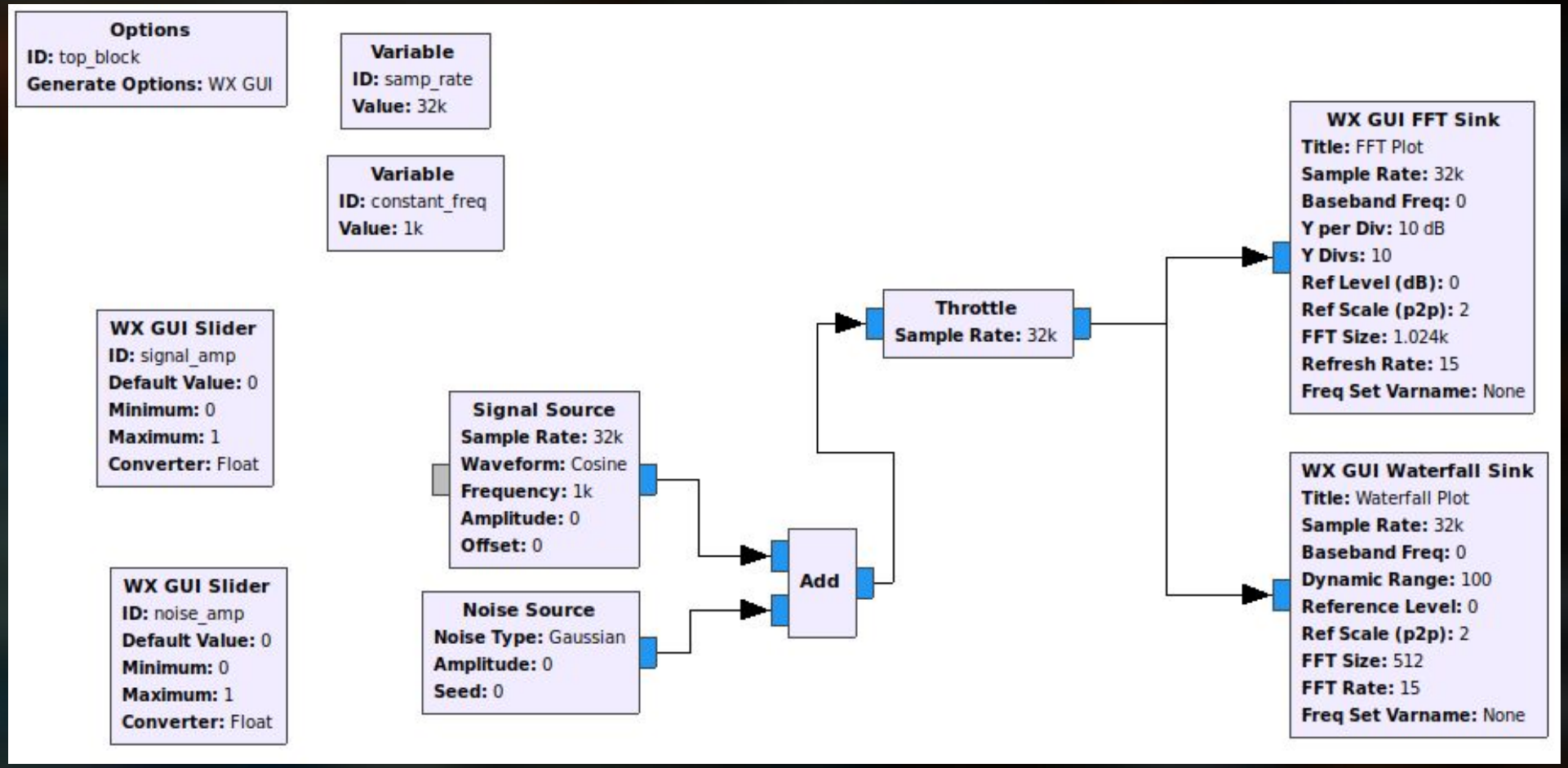
Generating Signals and Visualization



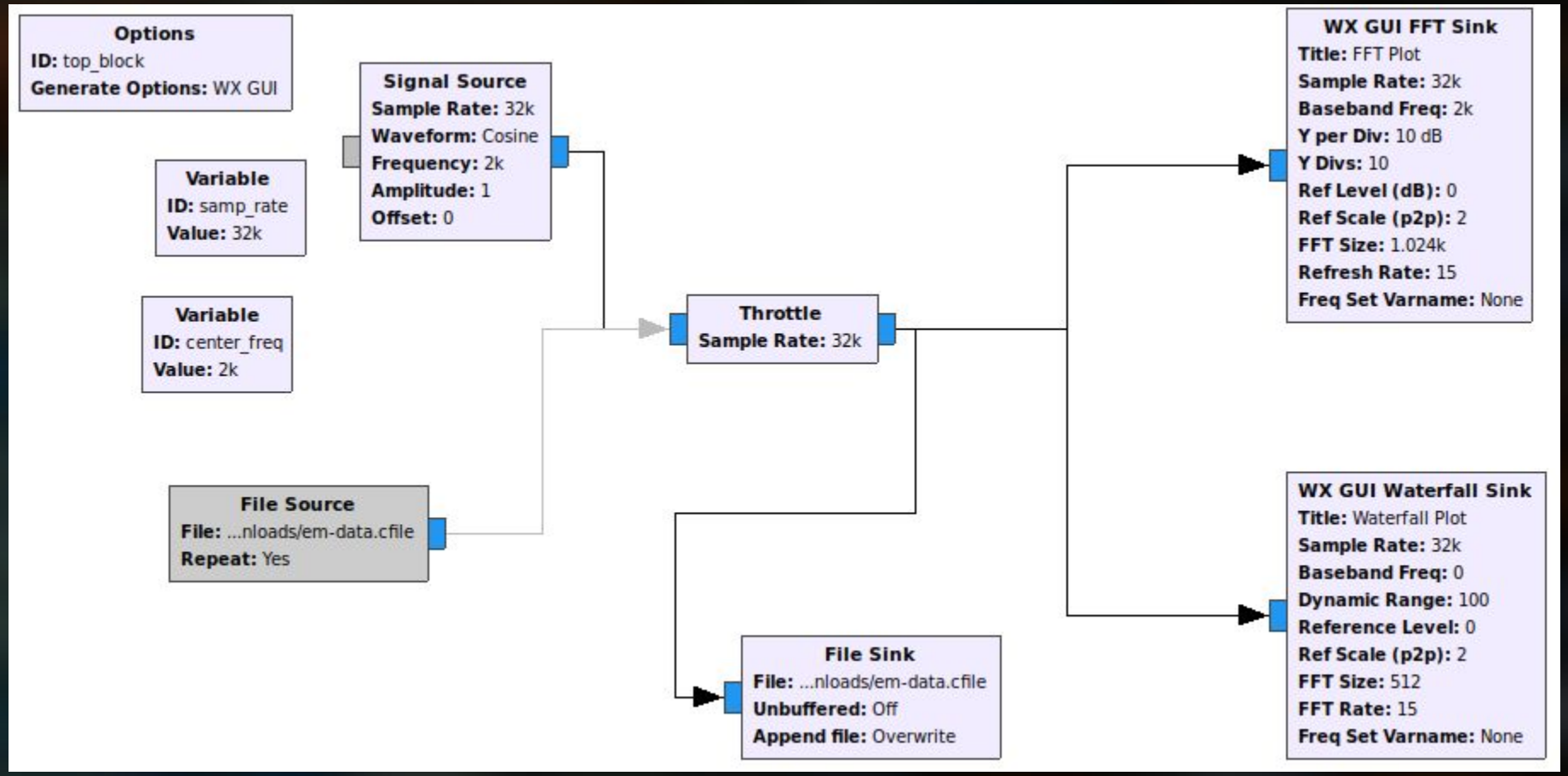
Audio Signals



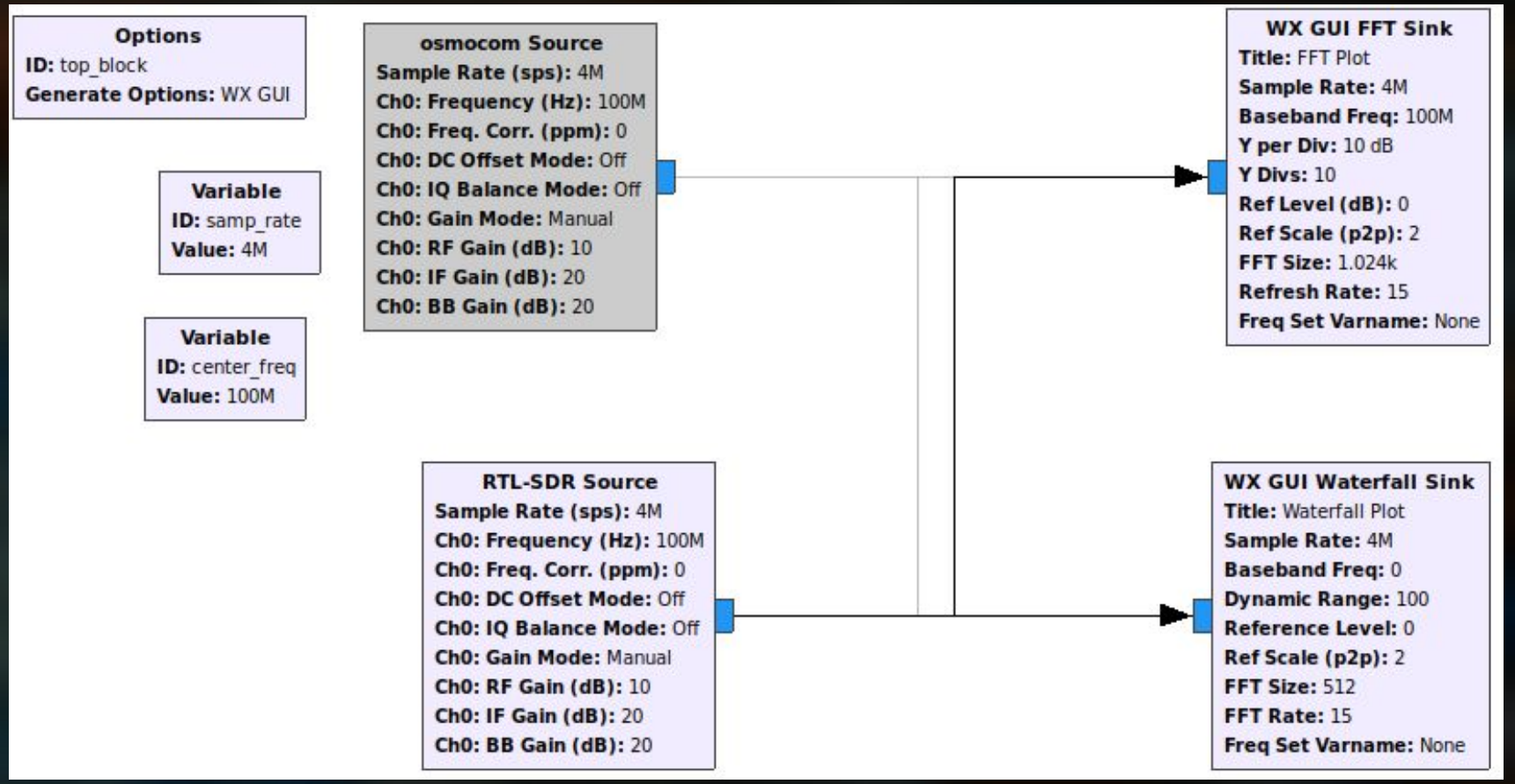
Signals vs Noise



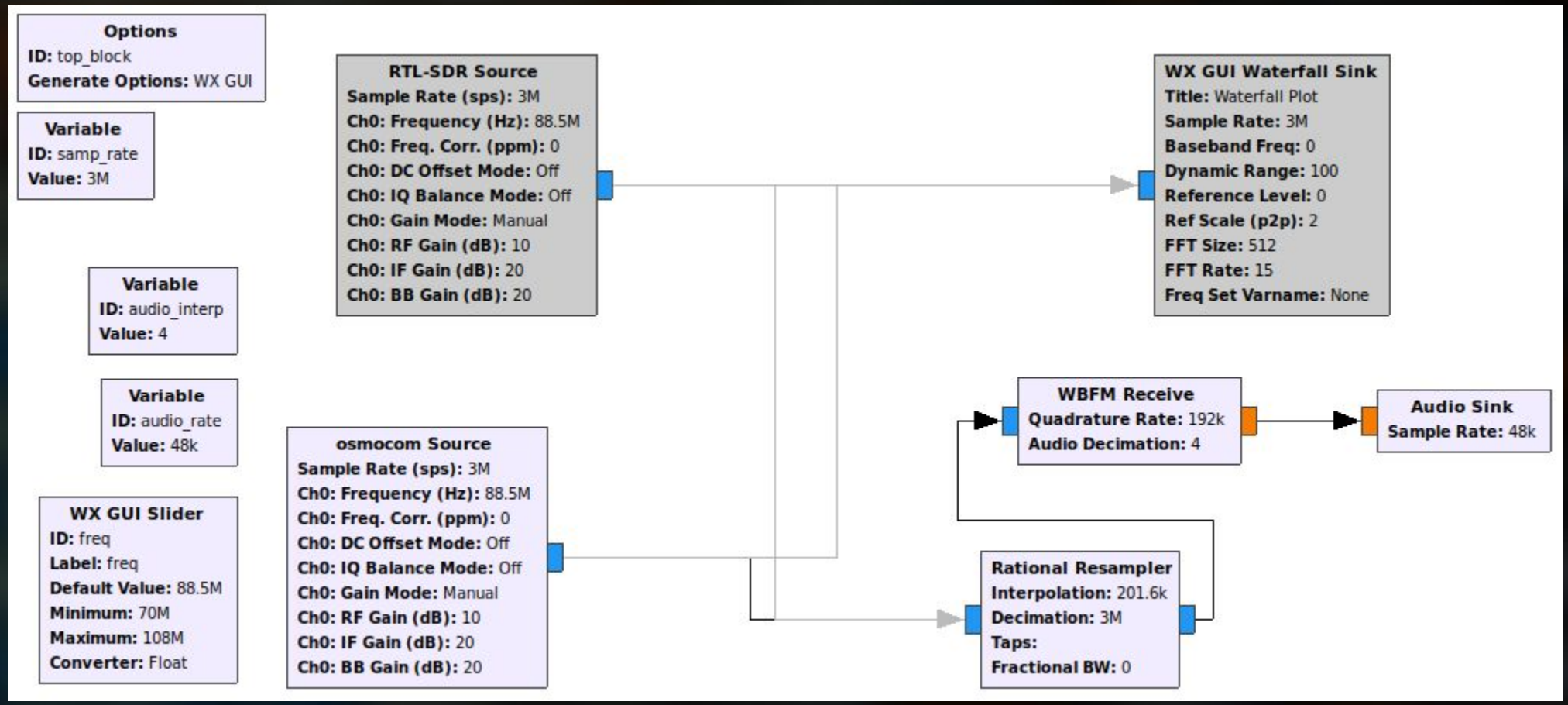
Saving EM data to files



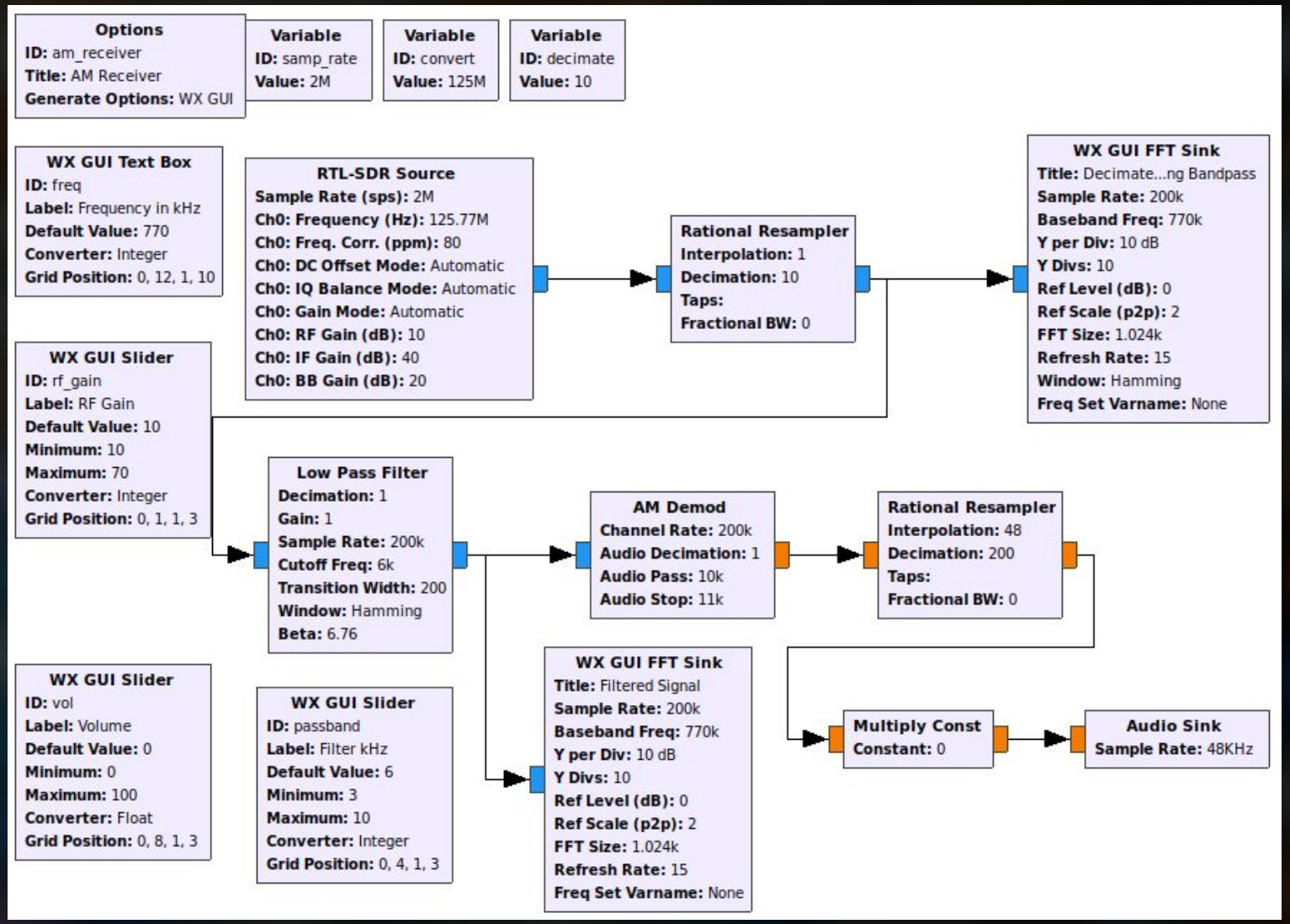
Reading data from SDR hardware



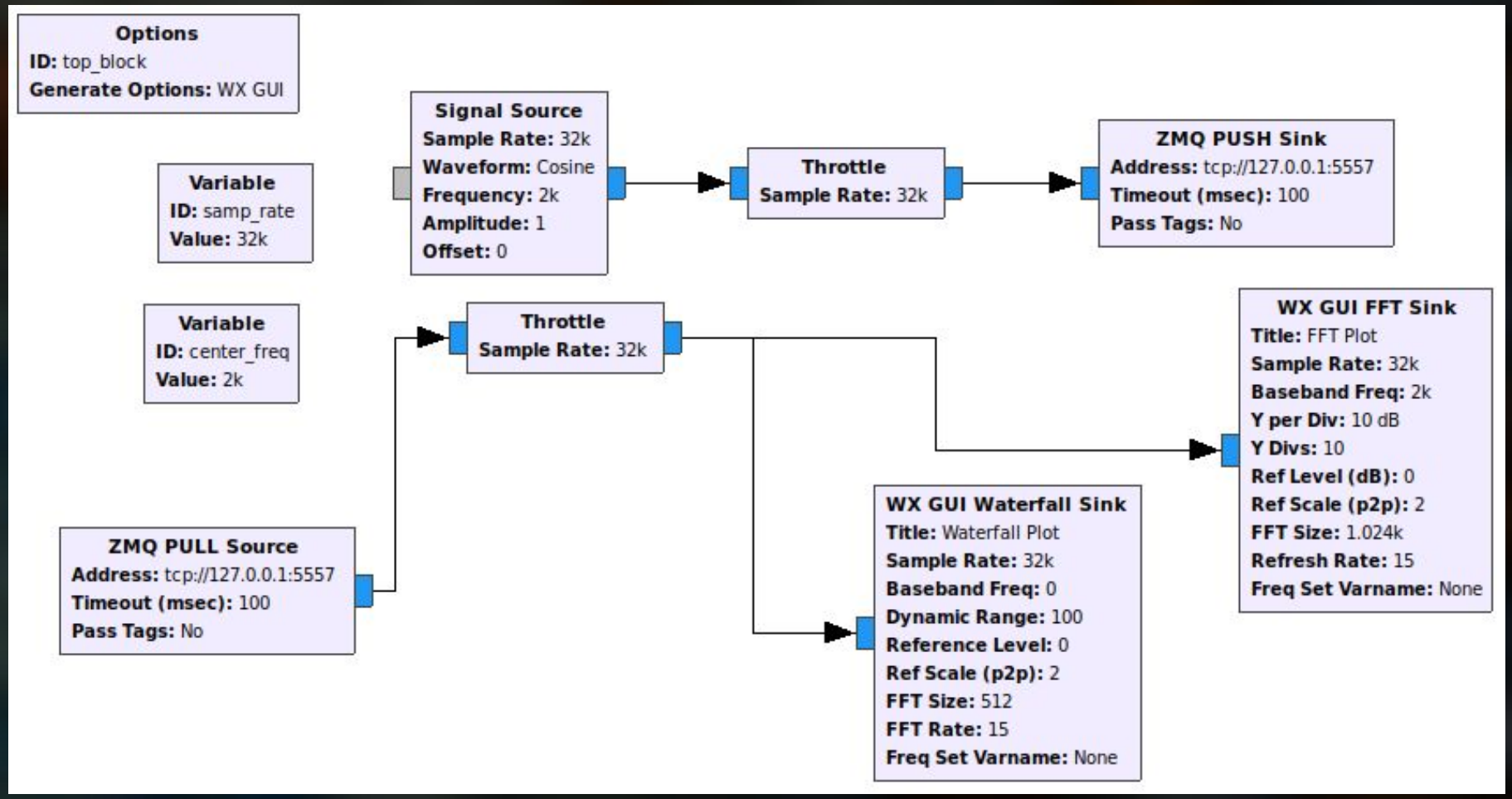
FM radio receiver



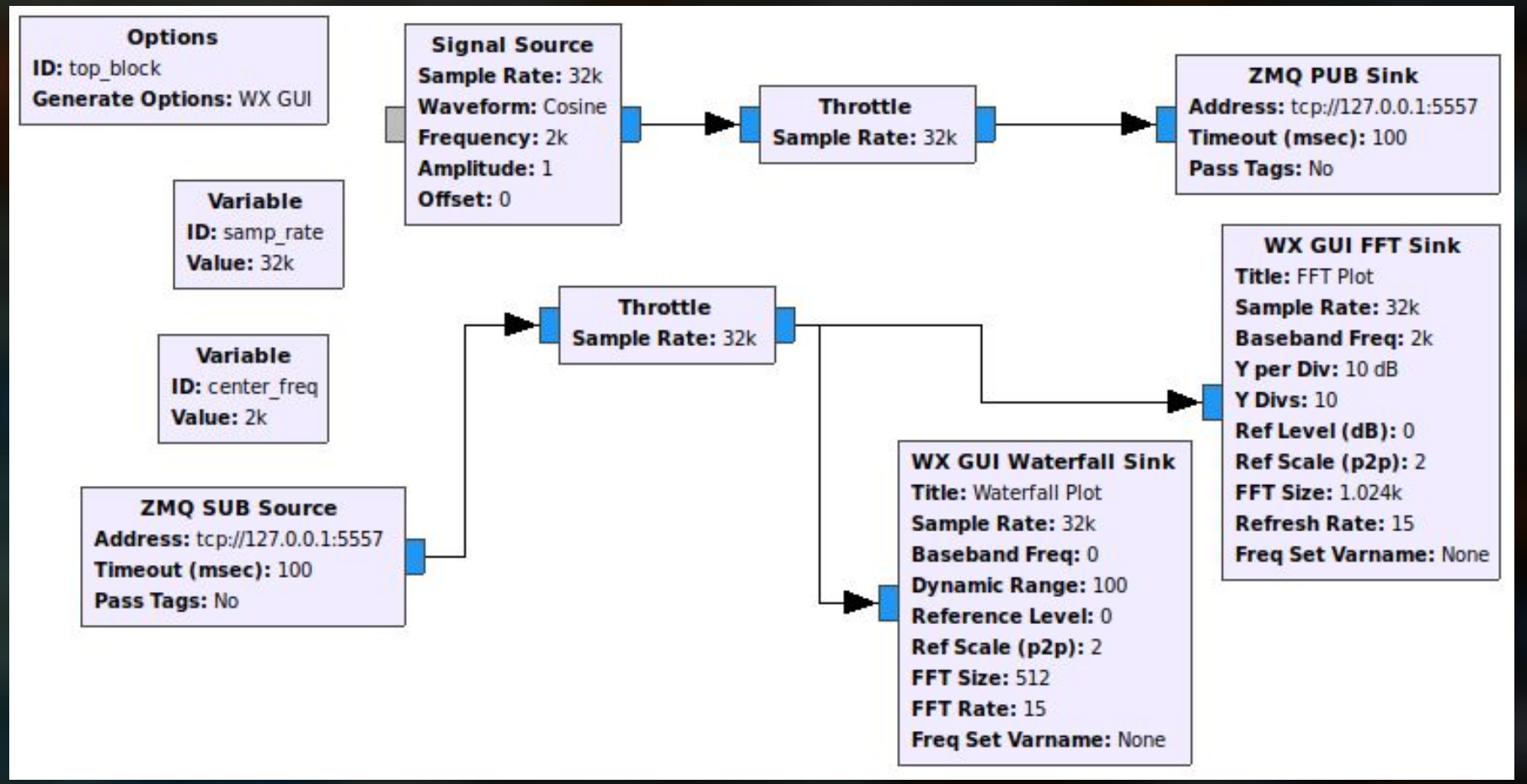
AM radio receiver



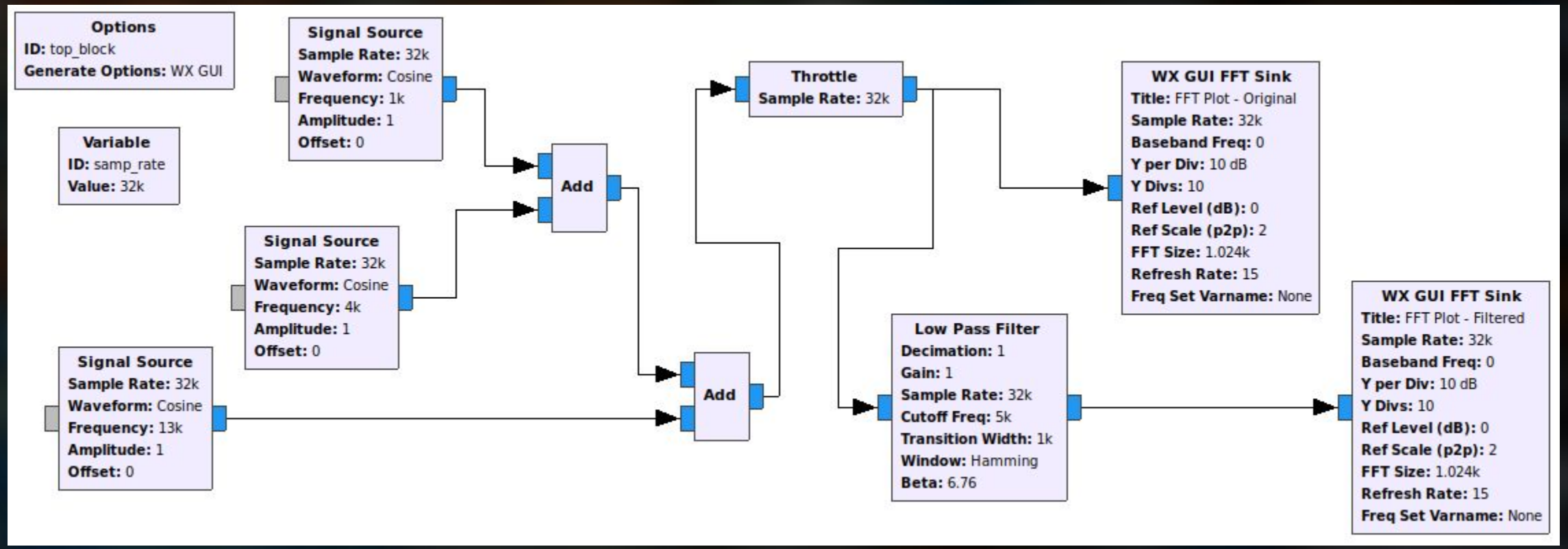
ZMQ PULL-PUSH Sockets



ZMQ PUB-SUB Sockets



Filters


Options
ID: top_block
Generate Options: WX GUI
Variable
ID: samp_rate
Value: 32k
Signal Source
Sample Rate: 32k
Waveform: Cosine
Frequency: 1k
Amplitude: 1
Offset: 0
Signal Source
Sample Rate: 32k
Waveform: Cosine
Frequency: 4k
Amplitude: 1
Offset: 0
Signal Source
Sample Rate: 32k
Waveform: Cosine
Frequency: 13k
Amplitude: 1
Offset: 0
Add
Add
Throttle
Sample Rate: 32k
Low Pass Filter
Decimation: 1
Gain: 1
Sample Rate: 32k
Cutoff Freq: 5k
Transition Width: 1k
Window: Hamming
Beta: 6.76
WX GUI FFT Sink
Title: FFT Plot - Original
Sample Rate: 32k
Baseband Freq: 0
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 1.024k
Refresh Rate: 15
Freq Set Varname: None
WX GUI FFT Sink
Title: FFT Plot - Filtered
Sample Rate: 32k
Baseband Freq: 0
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 1.024k
Refresh Rate: 15
Freq Set Varname: None

Exercises

1. Edit the **1.exercise.grc** flowgraph to only keep the 8 kHz by filtering out other signals with the help of suitable GRC blocks.

2. Create a GRC flowgraph called **2.exercise.grc** that reads the two given wav files (**siren-sound.wav** and **bikehorn-sound.wav**) and generate a new wav file called **mixed-signal.wav**. When this resulting file is played, we should hear the sounds of the two original files as the same time.

Software Defined Radio Programming (45 mins)

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Reading data through ZMQ to Python

- ▶️ See Jupyter-Notebook 1

Reading data from SDR hardware

- ▶️ See Jupyter-Notebook 2

Pre-processing EM data

- ▶️ See Jupyter-Notebook 3

Machine learning for EM data classification

- ▶️ See Jupyter-Notebook 4

Arduino program classification

- ▶️ See Jupyter-Notebook 5

Module Development for EMvidence Framework (45 mins)

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