

Beyond Static Signatures: Statistical Analysis of Radio Fingerprint Mutations

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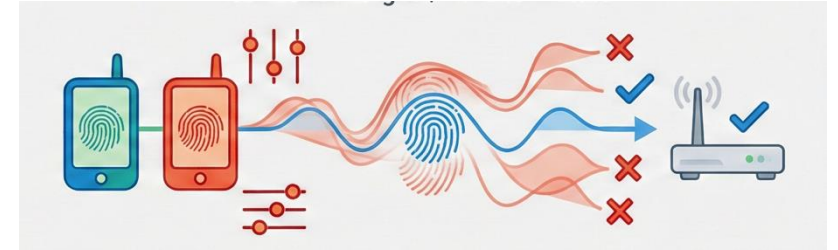
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Introduction & Core Problem

Assumption

Radio Frequency Fingerprinting (RFF) leverages hardware manufacturing imperfections for physical-layer device identification



The Problem

Recent research [1, 2] challenges the assumption of static fingerprints



[1] Alhazbi Saeif, Sciancalepore Savio, and Oligeri Gabriele. 2023. **The Day-After-Tomorrow: On the Performance of Radio Fingerprinting over Time.**

39th Annual Computer Security Applications Conference (ACSAC '23).

[2] M. Irfan, G. Oligeri and S. Sciancalepore. 2025. **Shifting Signatures: The Ephemeral Nature of the Radio Fingerprint on the USRP X310.**

13th IEEE Conference on Communications and Network Security (CNS '25).

Controlled Experimental Setup

Root cause of fingerprint mutations

FPGA image reloads on Software Defined Radios (SDRs)

Hardware

12 USRP b200-mini-i (Transmitters)
1 USRP X410 (Receiver)

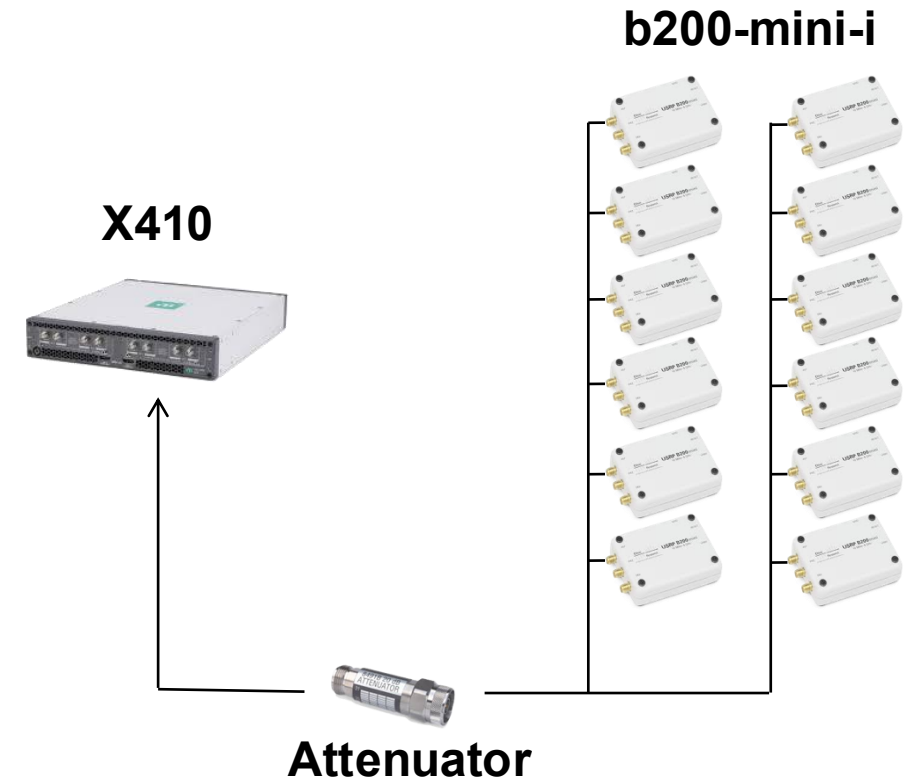
Link

50cm RF cable with a 20dB attenuator

Methodology

Three scenarios:

1. No reload
2. TX reload
3. RX reload

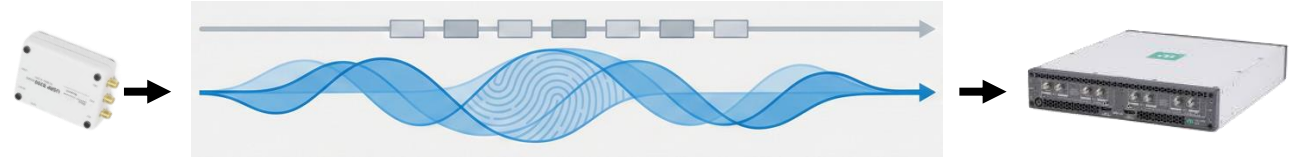


	N. TX	N. RX	FPGA reload	N. Meas.	Meas. Duration [Minutes]
<i>no-reload</i>	12	1	No	1200	4
<i>tx-reload</i>	12	1	TX	1200	4
<i>rx-reload</i>	12	1	RX	1200	4

100 measurements for each TX

Signal Processing & Deep Learning Pipeline

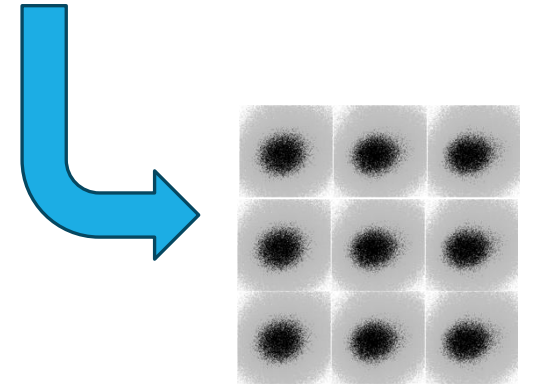
Waveform



BPSK modulation (128,000 sps), carrier $f_c = 900$ MHz

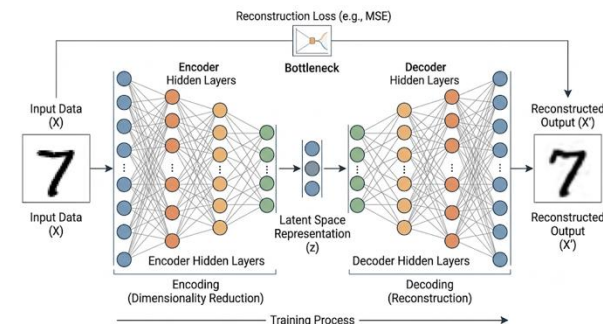
Pre-Processing

IQ samples mapped into 224 x 224 grayscale bi-variate histograms (images)



Classifier

Sparse autoencoder implementation in MATLAB R2023a



A New Formal Distance Metric

Mean Squared Error (MSE)

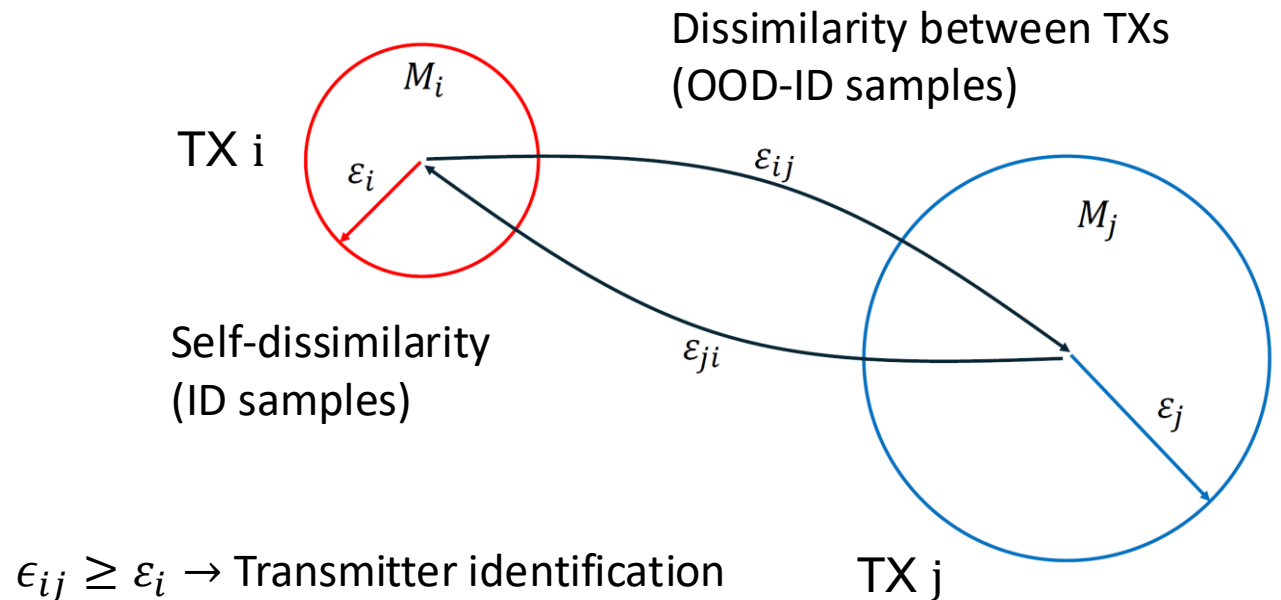
- $\alpha = \mathcal{T}(a)$
 - $\mathcal{R}_\alpha(b) = b'$
 - $\epsilon_i = \text{MSE}(b, b')$
- a and b represent the 60/40 splits of the dataset
 - $\mathcal{T}(\cdot)$ is the training process, and
 - $\mathcal{R}_\alpha(\cdot)$ is the reconstruction function leveraging the model α

It is not possible to compare ϵ_{12} with ϵ_{23}

since the baseline are different: $\epsilon_1 \neq \epsilon_2$

Scale-Invariant Distance

$$\delta_{ij} = \begin{cases} \sqrt{\frac{|\epsilon_{ij} - \epsilon_i|}{\epsilon_i}} & \text{if } i \neq j, \\ 0 & \text{otherwise.} \end{cases}$$



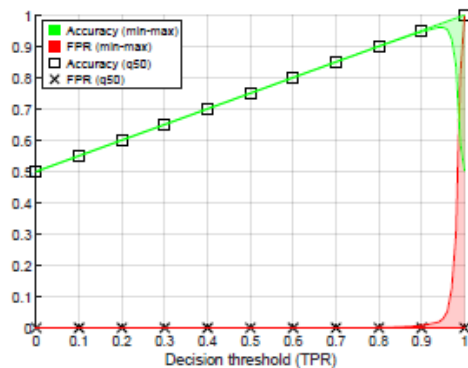
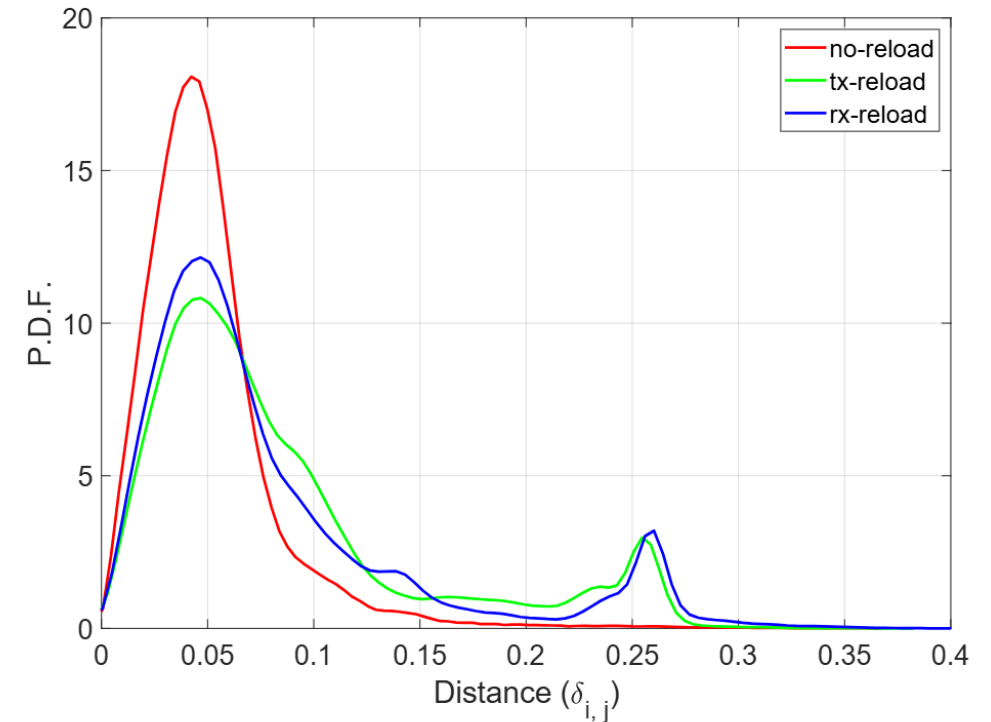
The "Two Fingerprints" Phenomenon

Finding

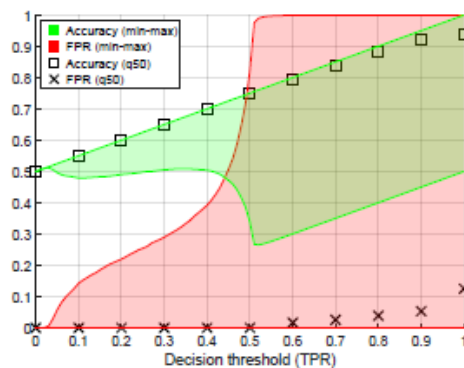
- No-reload: standard behavior, 1 peak, 1 fingerprint
- TX/RX reload: 2 peaks, 2 fingerprints

Performance variance

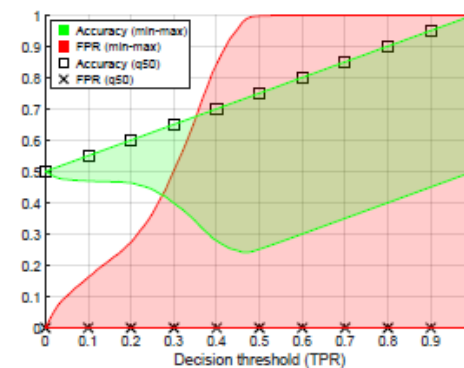
- Random False Positive Rates (FPR) during reloads
- No substantial fingerprint difference between TX and RX reloads



No reloads



TX reloads



RX reloads

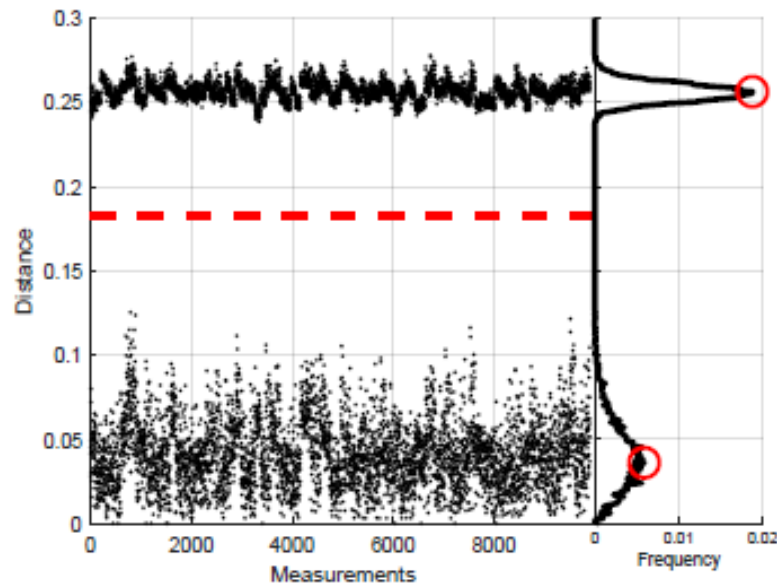
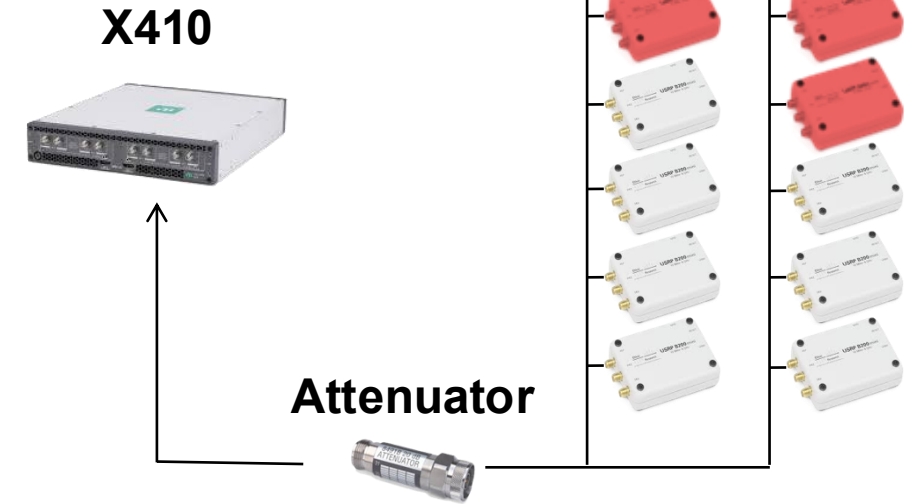
Statistical Modeling of Mutations (1/2)

5 out of 12 transmitters exhibit dual states.



$M_1, M_2, M_3, M_4, \dots, M_{100}$

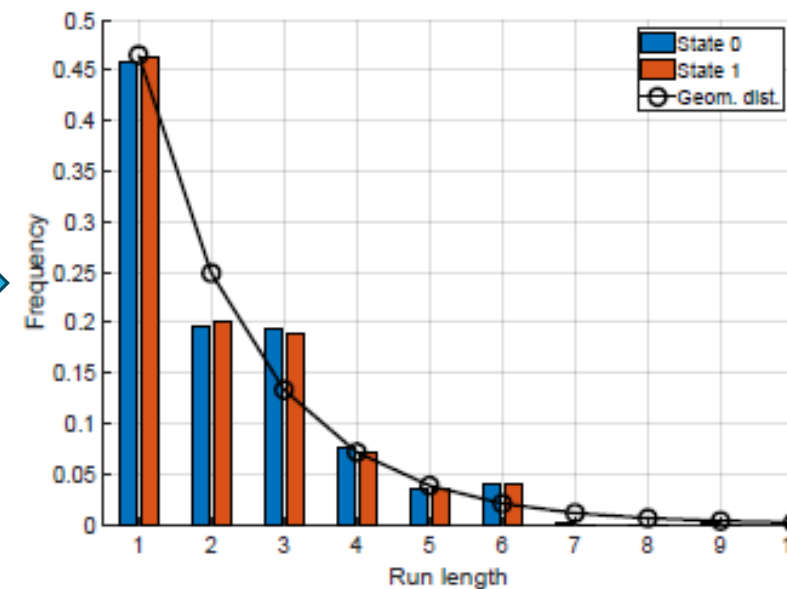
Let us consider all the possible comparisons when considering **transmitter 12**: $100 \times 100 = 10^5 \dots$ and the associated δ_{ij}



State 1



State 0

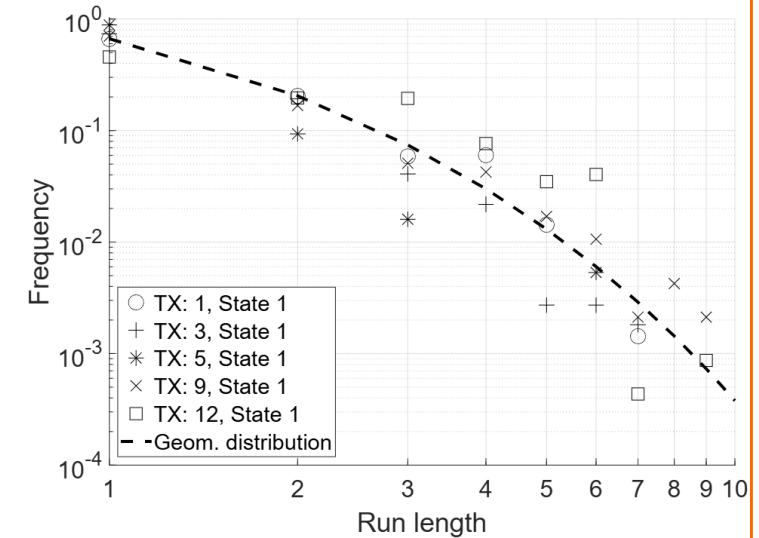


Statistical Modeling of Mutations (2/2)

Let us now consider all the 5 transmitters affected by the phenomenon

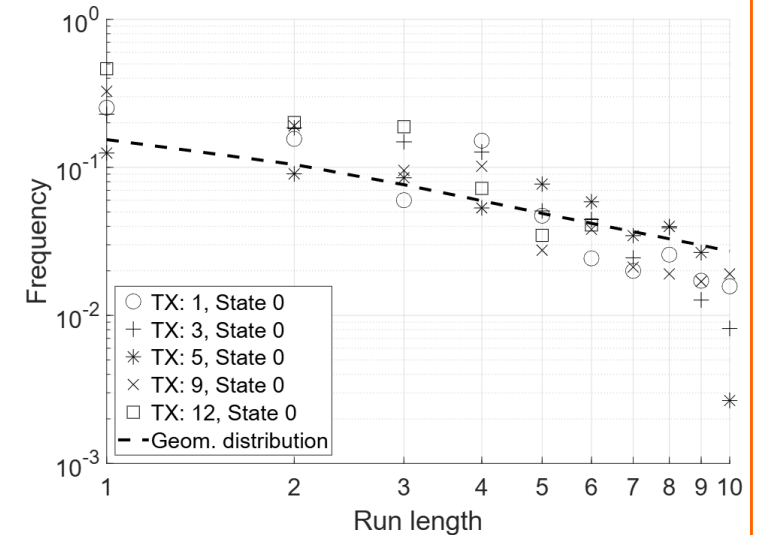
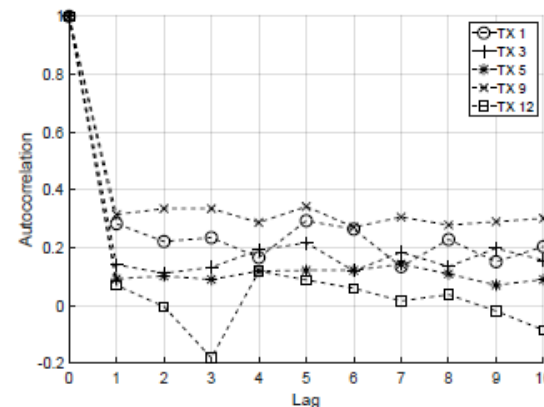
State 1

Memoryless (Markovian), fits a geometric distribution



State 0

Retains temporal dependencies (autocorrelation)



Root Cause Analysis (Synchronization)

Hypothesis

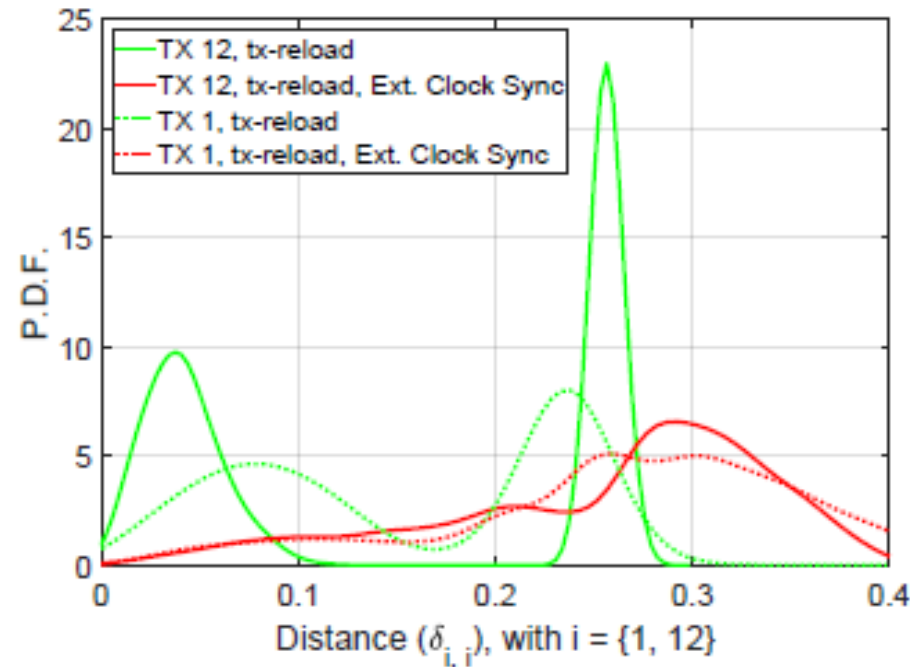
Mutations arise from the residual phase and timing synchronization errors.

Validation

Experiments utilizing an external 10MHz reference clock (USRP OctoClock CDA-2990)

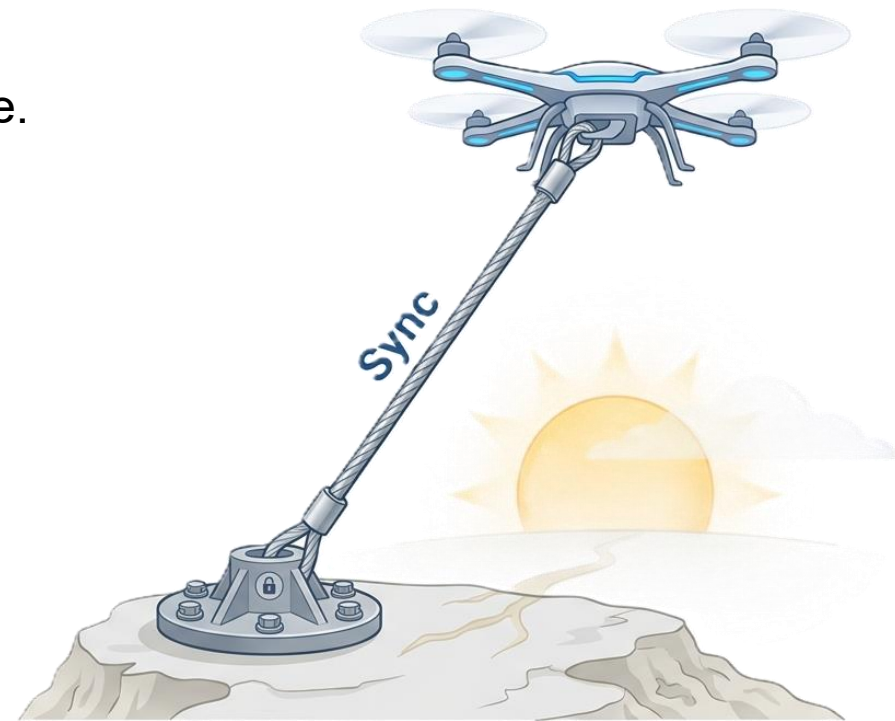
Result

Dual-state mutations completely disappear



Limitations and Real-World Applicability

- External synchronization is impractical for real-world deployments.
- Our study is limited to SDR testbeds
- Long-term environmental drift is outside the current scope.



Conclusion

- RFF signatures are dynamic and probabilistic, not static
- Hardware events (reloads) induce measurable shifts and mutational patterns in RFF
- Robust classification requires accounting for synchronization-induced states

Questions?