Washington University in St. Louis
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Two Measure is Two Know: Calibration-free Full Duplex Monitoring for Software Radio Platforms

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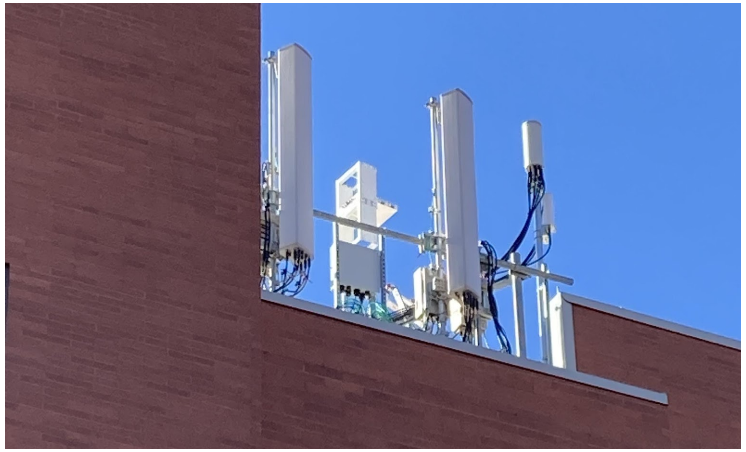
Motivation: Spectrum Sharing

Current Spectrum Use

Commercial user



Scientific user[1]

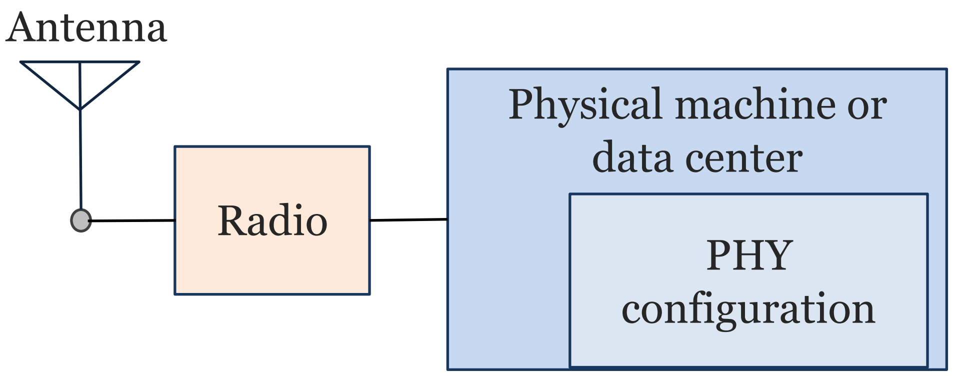
Public safety[2]

Spectrum is shared among many systems to increase the use efficiency.

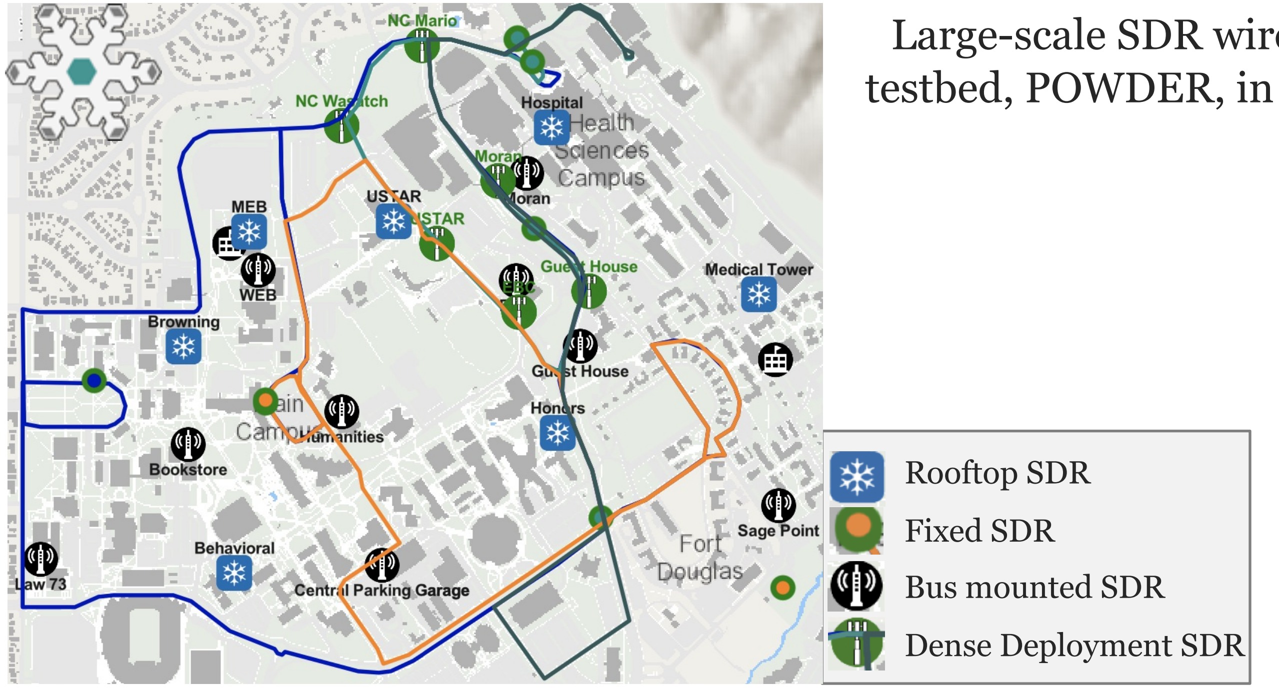
However, current sharing is largely separated across geographic areas and frequency bands

1. Wireless Innovation Forum, Passive and active spectrum sharing, tech report, 2020.
2. NOAA National Severe Storms Laboratory, https://www.nssl.noaa.gov/tools/radar/.

Further Sharing via Software Radio Platforms



Software Defined Radio (SDR) platform



Large-scale SDR wireless testbed, POWDER, in Utah[1]

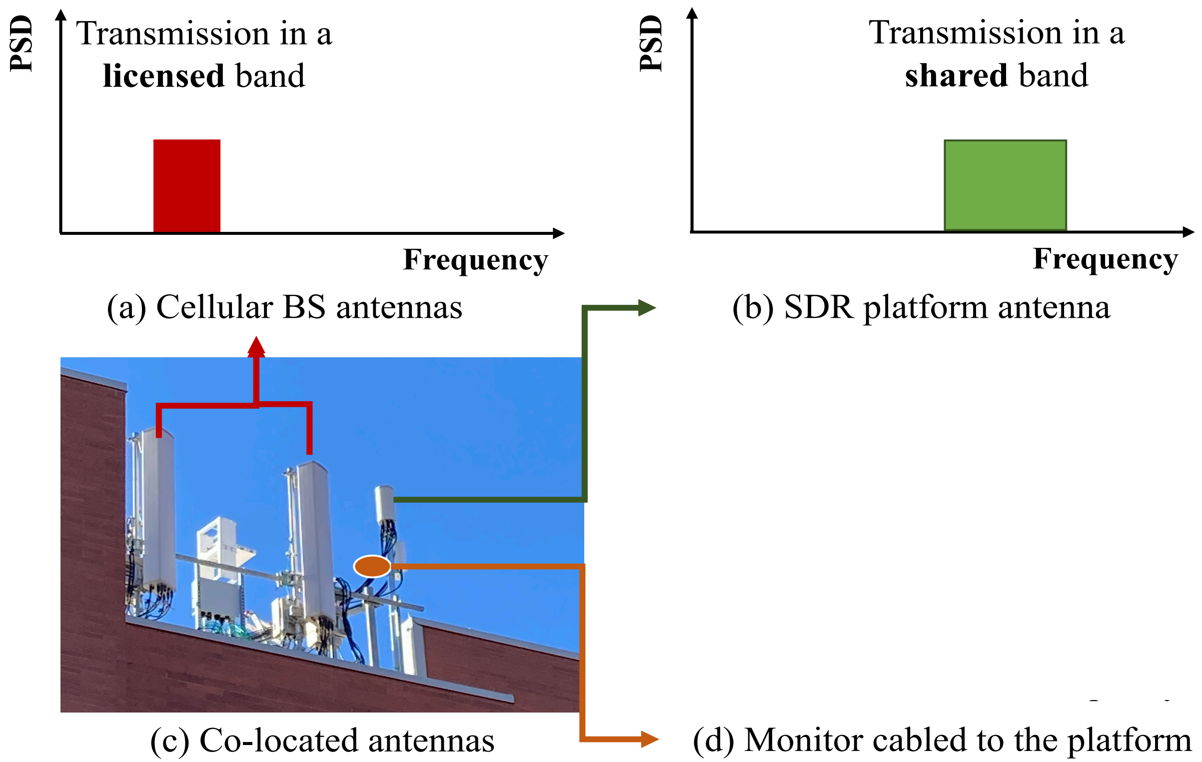
SDR platform's software configurability

- enables dynamic use of the spectrum temporally and geographically.
- is the key to unlocking more spectrum to satisfy the growing demand.

1. Breen et. al, POWDER: Platform for open wireless data-driven experimental research, Computer Networks, vol. 197. 2021.

Challenge: Spectrum Violation Risks

Challenge: Spectrum Violation



(a) Cellular BS antennas

(b) SDR platform antenna

(c) Co-located antennas

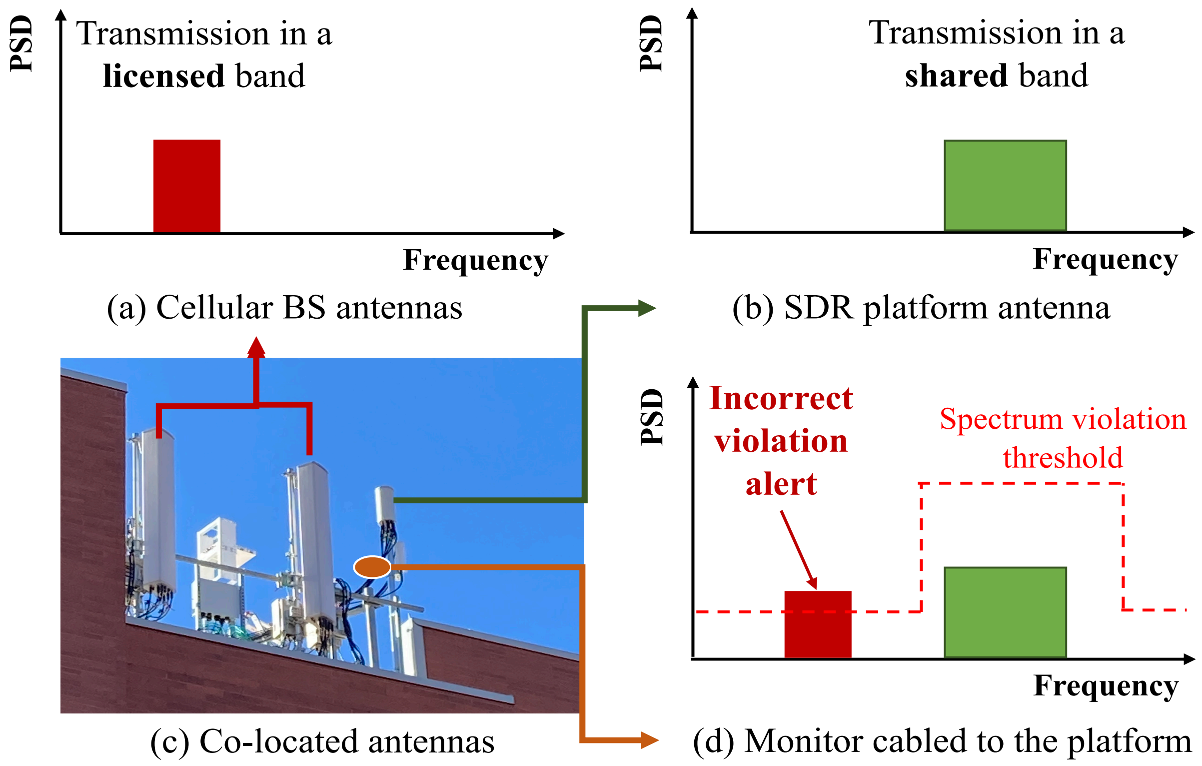
(d) Monitor cabled to the platform

1. SDR platforms share the spectrum with other (licensed) wireless operators, see (a).

2. POWDER has periodically received inquiries about interference from the wireless operators.

Accurate and continuous monitoring of actual spectrum use is critical to prevent interference to other users.

Spectrum Monitoring: Related Work



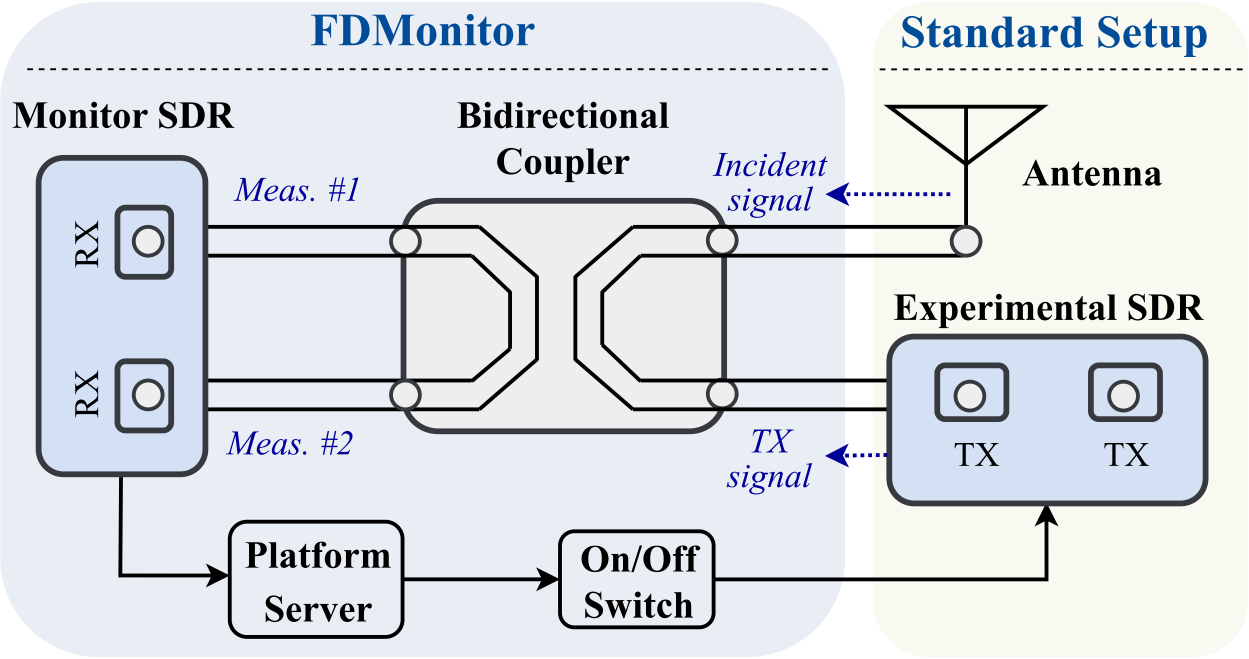
- Remote monitor: infeasible
  - cannot identify which signal is from the user
- Inline monitor: insufficient, see (d)
  - cannot separate the user's signal from the ones from the environment (incident signal)
- Software-based monitoring: insufficient
  - cannot monitor the exact analog signal due to nonlinearities in the RF hardware

This work proposes *FDMonitor*, a **f**ull-**d**uplex RF-based **monitor** for both user monitoring and environment monitoring

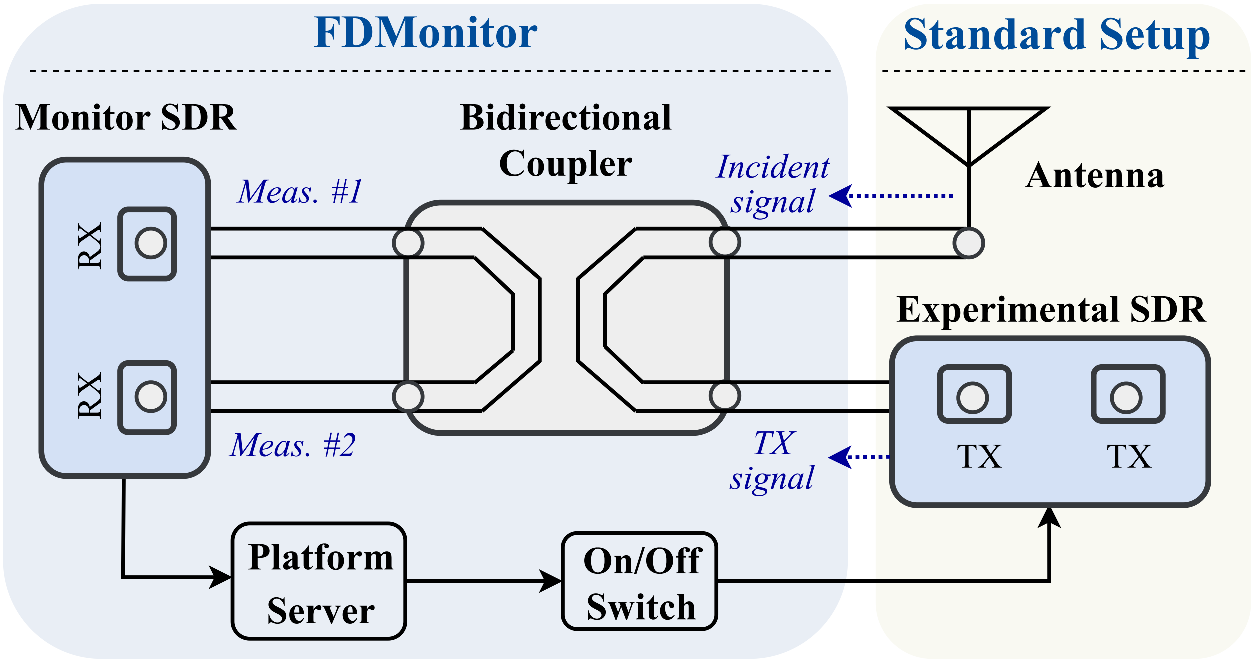
The Proposed System: FDMonitor

The Proposed FDMonitor System

Architecture and the closed-loop control of FDMonitor



The Proposed FDMonitor System

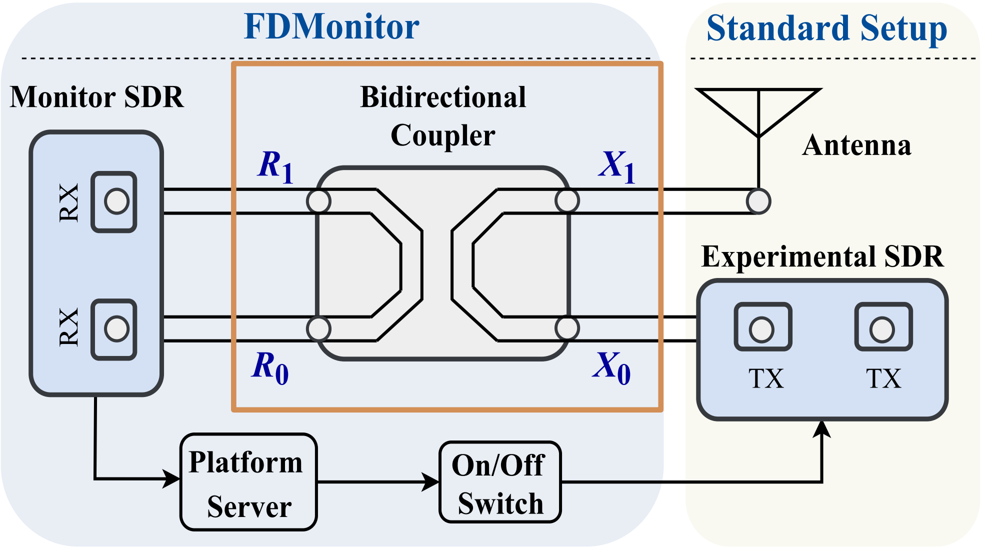


Architecture and the closed-loop control of FDMonitor

Advantages:

- No need of transmitted or incident signal priors.
- It estimates the system on the fly without calibration.
- Robust across *signal type, carrier frequency, bandwidth and transmit power*.
- Enable *full-duplex monitoring* of the transmitted and the incident signals.

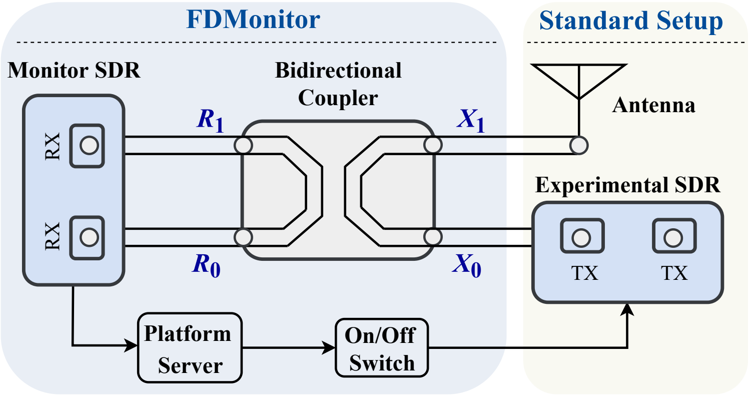
FDMonitor: Hardware Design



Hardware: custom 6GHz wideband bidirectional system

- X_0, X_1: transmitted/incident signals. R_0, R_1: directional coupler outputs.
- **Issue**: imperfect matching of radio frequency (RF) subsystems over the wide bandwidth.
- **Result**: R_0, R_1 are directionally mixed signals of X_0, X_1.

FDMonitor: Source Separation



Frequency-domain Blind Source Separation (BSS) Modeling

FDMonitor models the separation problem as *frequency-domain BSS:*

$$\boldsymbol{R} = \boldsymbol{A}\boldsymbol{X} + \boldsymbol{V}$$

where $R_{i\in\{0,1\}}$ is the frequency-domain components via DFT, $\boldsymbol{R} = [R_0, R_1]^T$, $\boldsymbol{X} = [X_0, X_1]^T$, and $\boldsymbol{V} \sim \mathcal{CN}(\boldsymbol{0}, N\sigma^2\boldsymbol{I})$. N is the number of samples.

Goal: Estimation of $\boldsymbol{A}$ and $\boldsymbol{X}$.

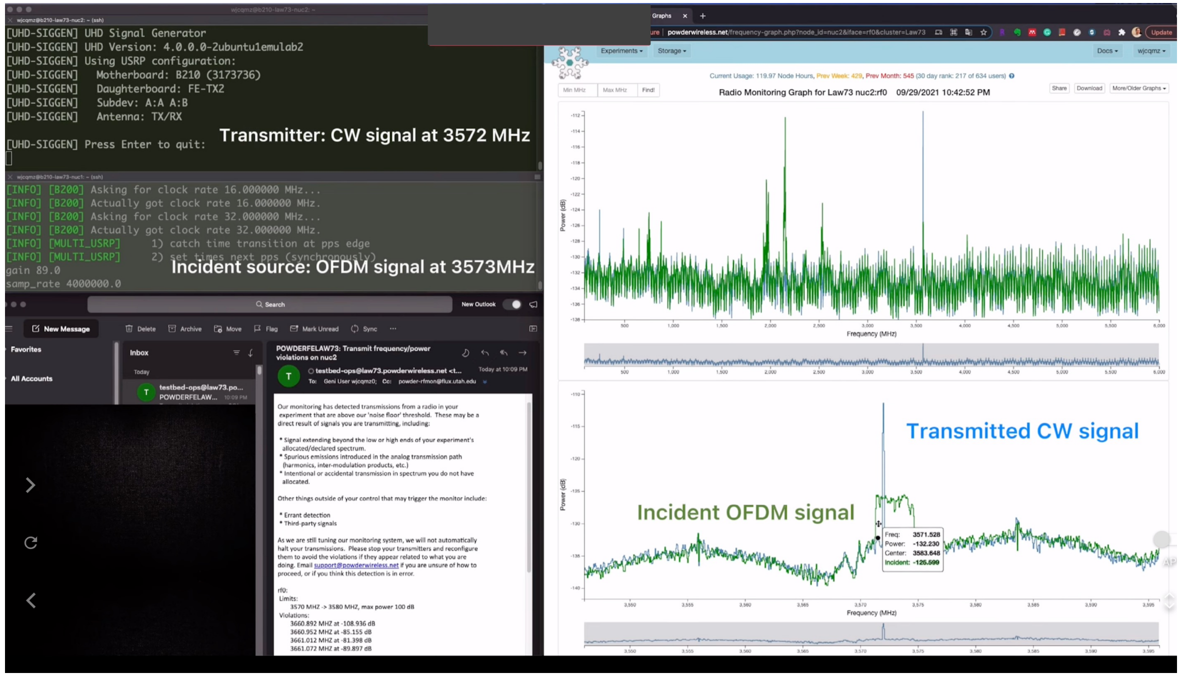
Solution: (1) Complex-valued Independent Component Analysis (ICA)

(2) Scaling and permutation alignment of $\boldsymbol{X}$ estimate

Deployment and Evaluation

Real-world Deployment of FDMonitor

FDMonitor has been deployed on POWDER for 24/7 monitoring of 19 shared SDR platforms for 3 years.

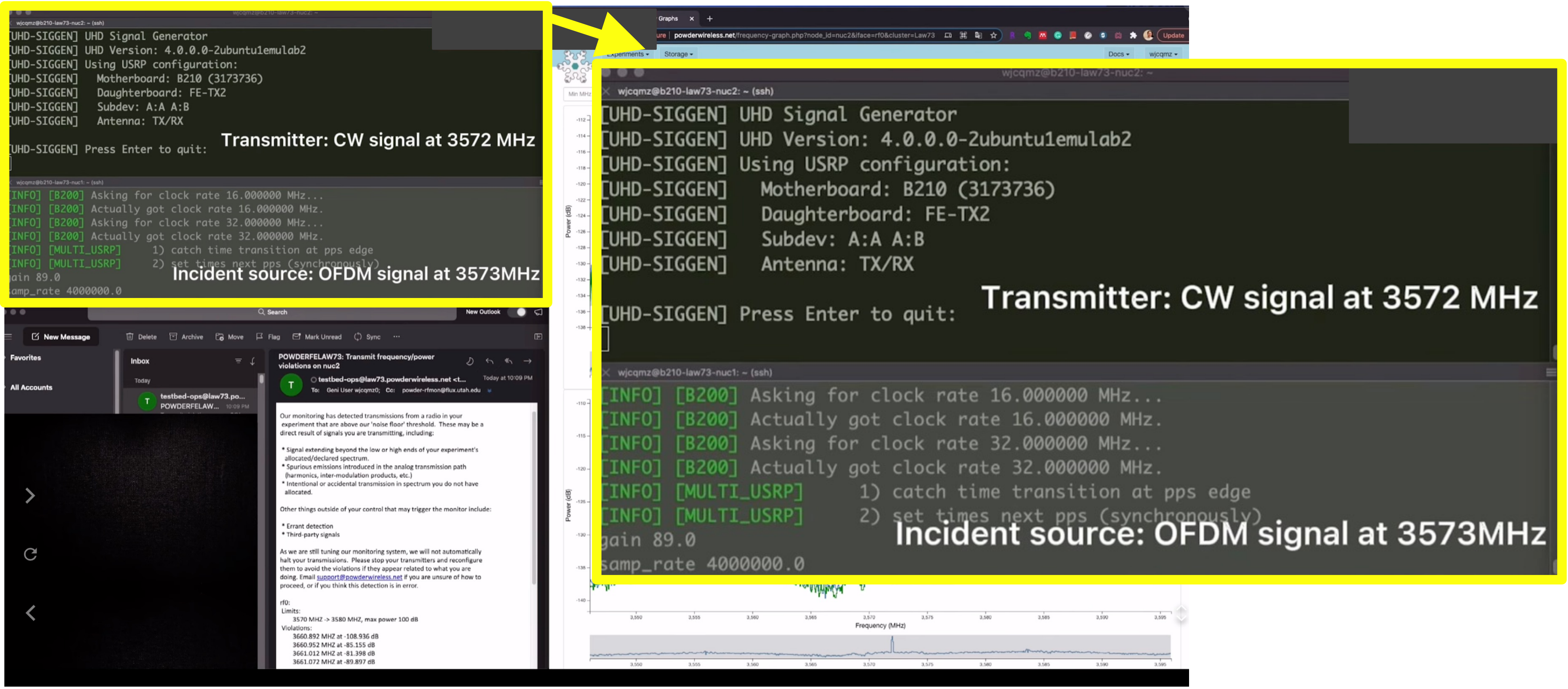


An example of FDMonitor's closed-loop workflow

1. J. Wang, et al., "A Compliance Monitoring System for Open SDR Platforms," ACM Conference on SenSys, 2021.

Real-world Deployment of FDMonitor

1. Users: terminal access to two SDR platforms.



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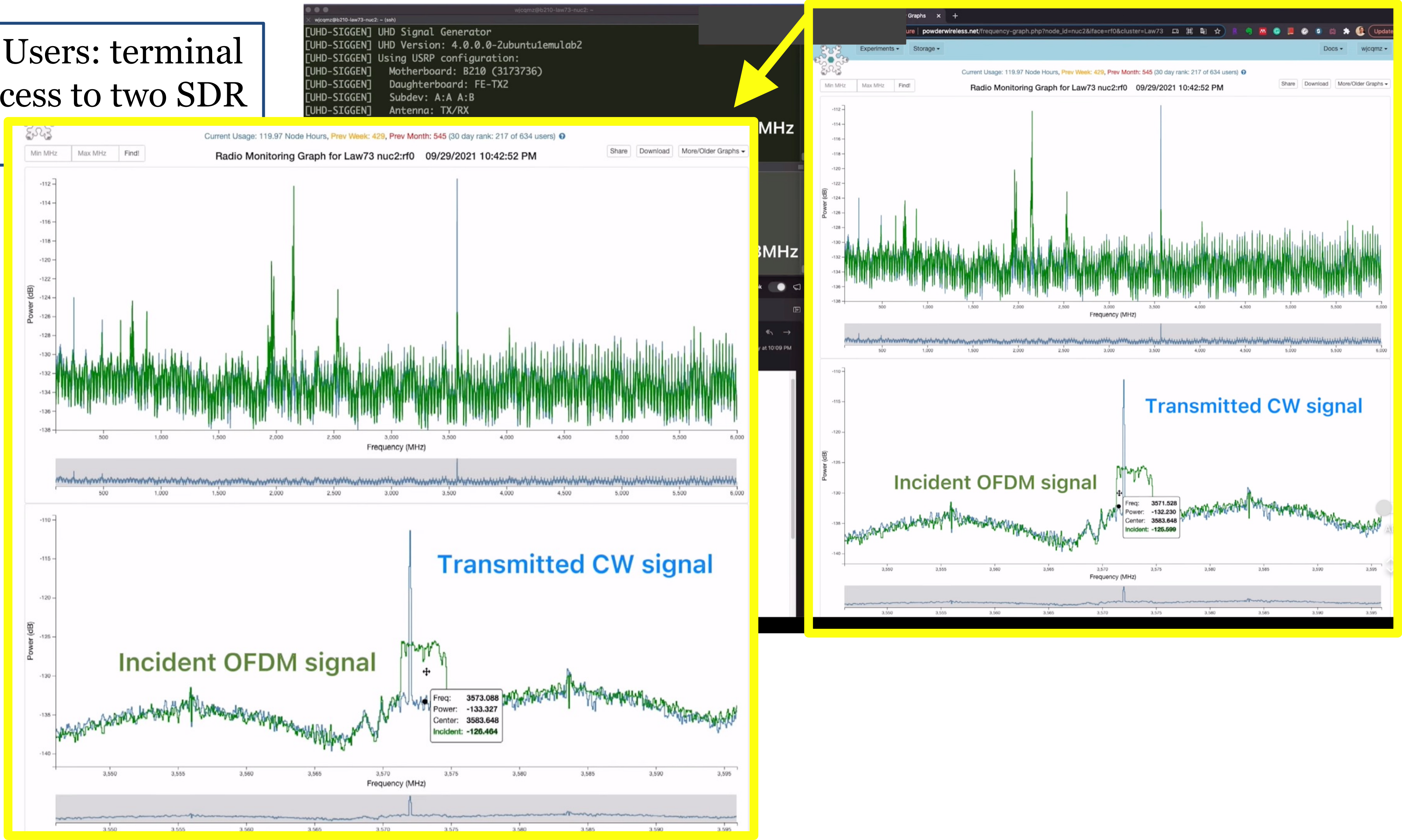

2. FDMonitor: PSD graph webpage for separated signals.

Real-world Deployment of FDMonitor

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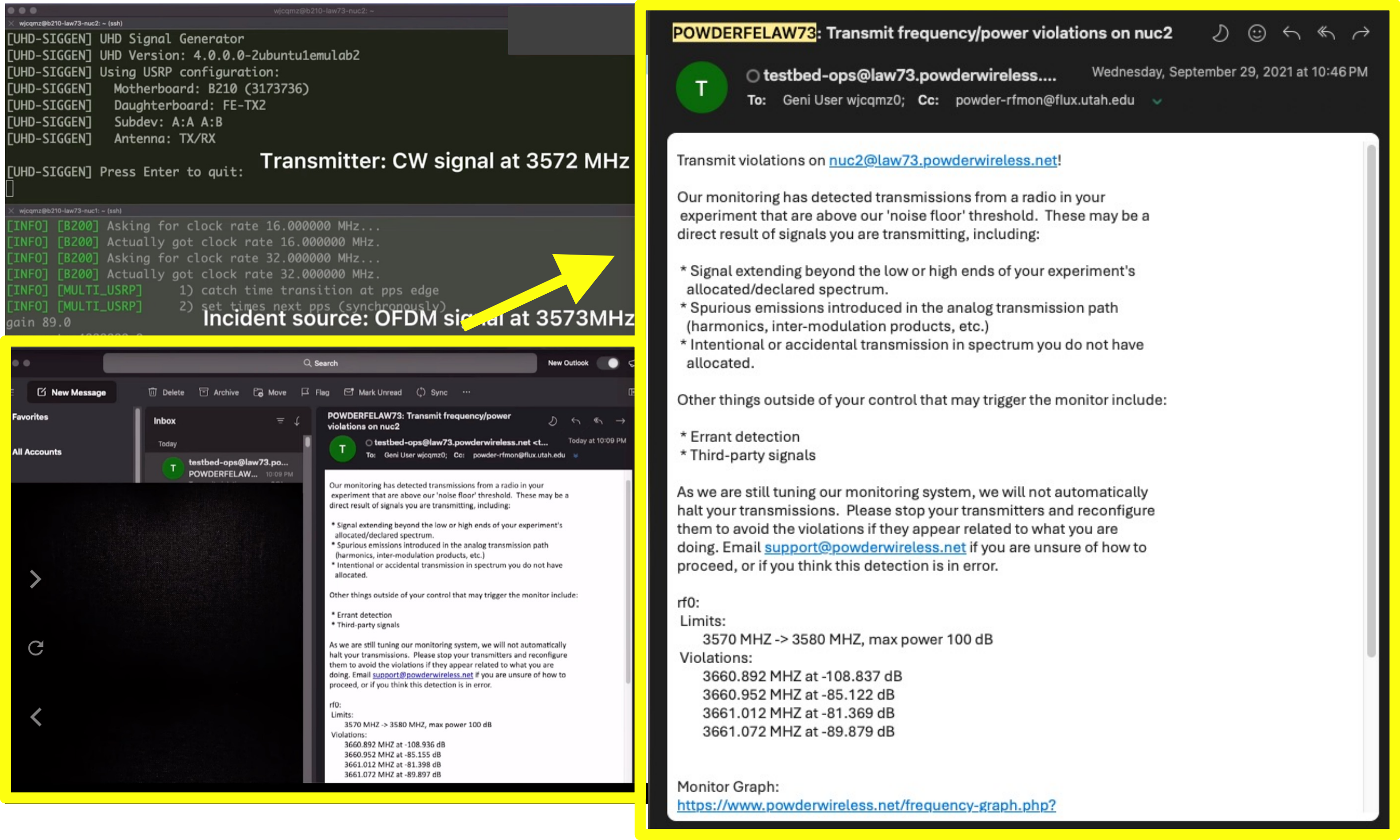


2. FDMonitor: PSD graph webpage for separated signals.

3. FDMonitor: Real-time violation alerts via email.

FDMonitor has been deployed as a closed-loop solution on POWDER for continuous monitoring of 19 shared SDR platforms for 3 years.

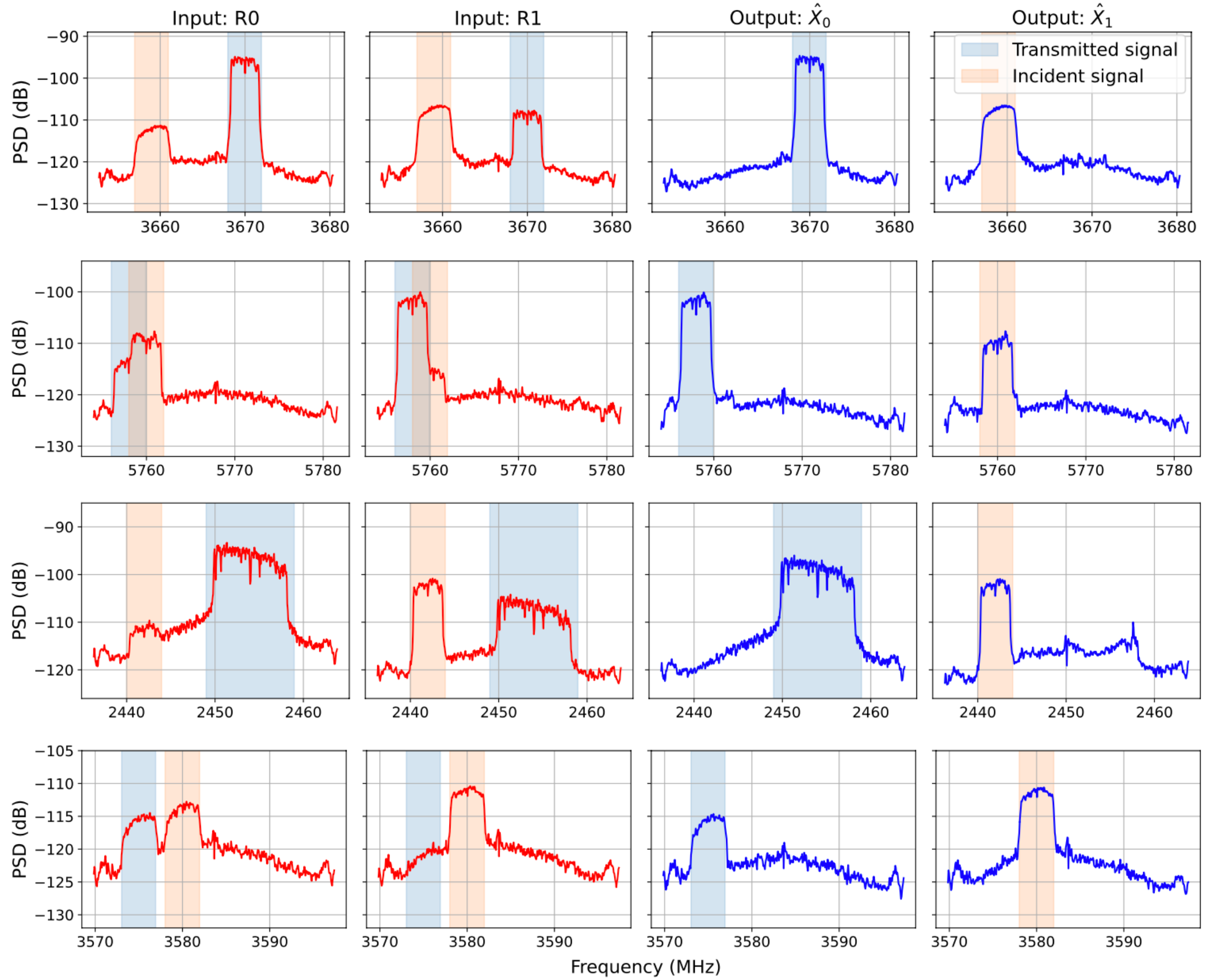
Evaluation: Two Measure to Two Know

(a) Signal type

(b) Freq. overlap

(c) Signal bandwidth

(d) Signal power



Experiments have shown that FDMonitor can separate and identify transmitted vs. incident signals of *different modulations, center frequencies and bandwidths, and relative power levels.*

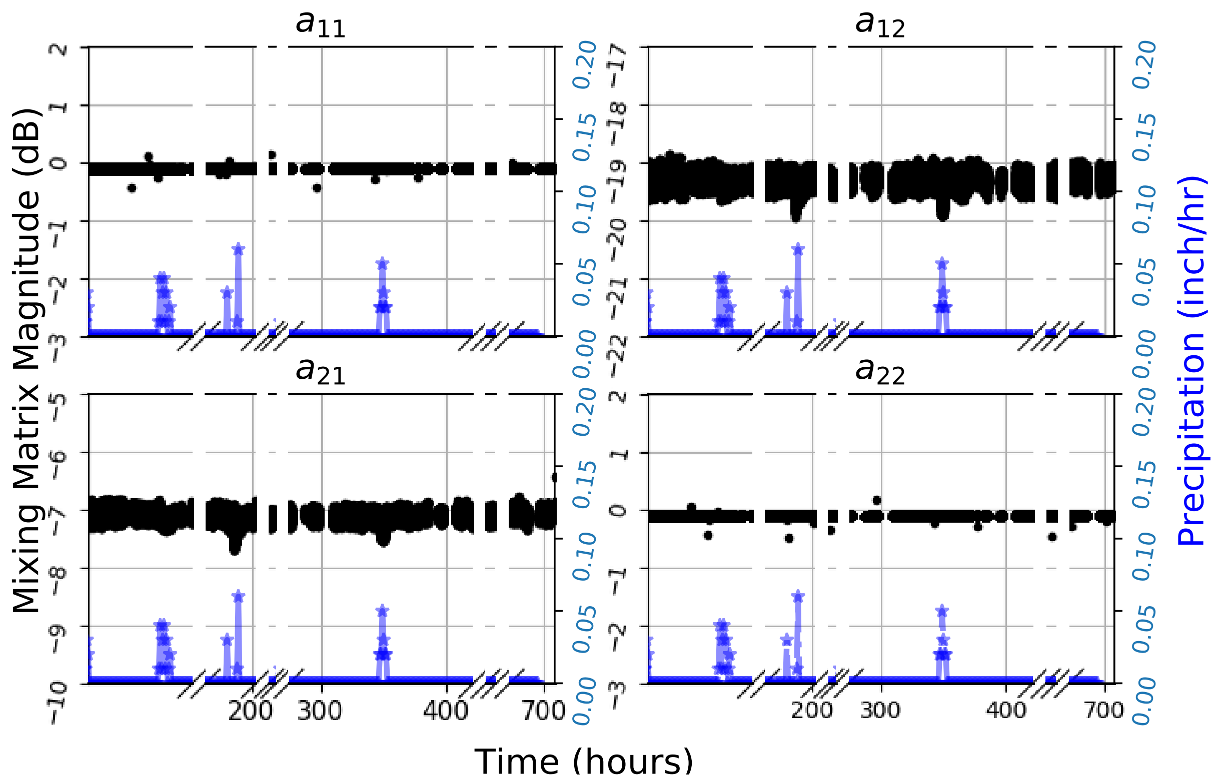
Evaluation: More Source Separation Tests

	Transmitter	Incident Source
Signal Types	OFDM/CW/BPSK	BPSK/OFDM/CW
RX Center Frequency	2.4/5.8/3.5GHz Band	2.4/5.8/3.5GHz Band
Signal BW (MHz)	1-10	4
Transmit Gain (dB)	10-80	45

Extensive experiments to verify that FDMonitor can *robustly separate and identify* signals of different RF configurations.

Evaluation: Mixing System vs. Precipitation

Mixing matrix magnitude over 105 hours with precipitation data



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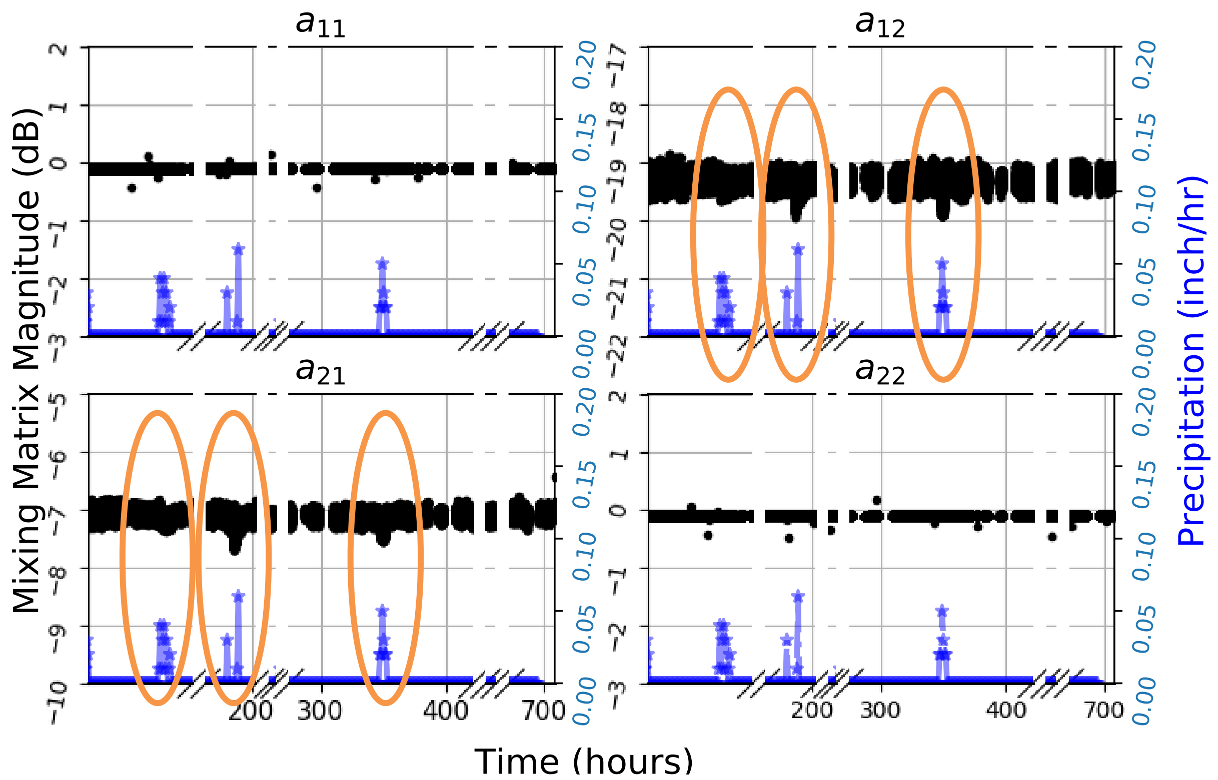
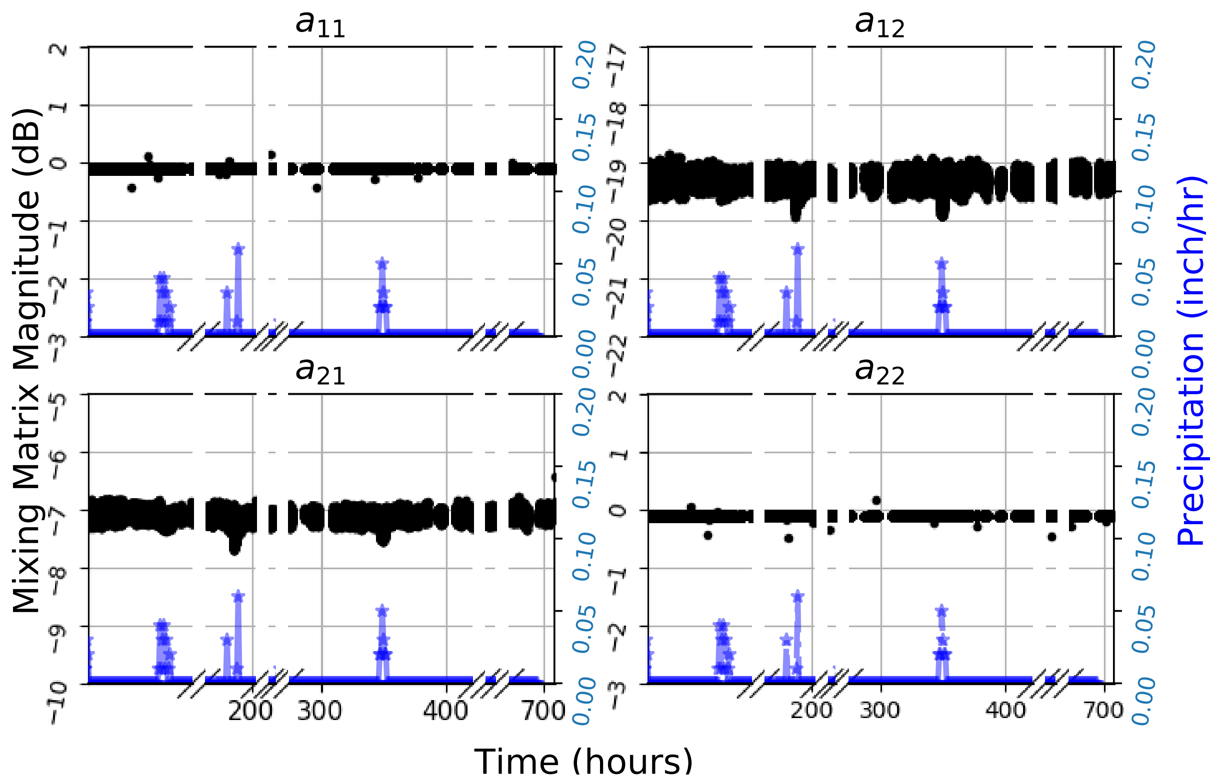


- The magnitude of a_{12} and a_{21} decreases when rain starts and later goes back to the same pre-rain level.
- ~1 dB magnitude decrease means that 26% less of the mixed signal is used for separation.

Evaluation: Mixing System vs. Precipitation

Mixing matrix magnitude over 105 hours with precipitation data



FDMonitor estimates the mixing system on the fly and therefore is adaptive to weather changes.

System-wide 27-Month Evaluation

FDMonitor alert accuracy during continuous monitoring of 19 shared SDR platforms for 27 months.

Type	False positives: 45 emails		True positives: 944 emails				
Rate	False discovery rate (FDR): 4.6%		Positive predictive value (PPV): 95.4%				
Cause	Bug: Spectrum declaration lost	Permutation ambiguity	No spectrum declaration/ TX-declaration mismatch	High gain induced harmonics	Signal spillover	Intermodulation distortions	System testing
Rate	62.2%	37.8%	58.2%	23.0%	0.8%	13.1%	4.9%

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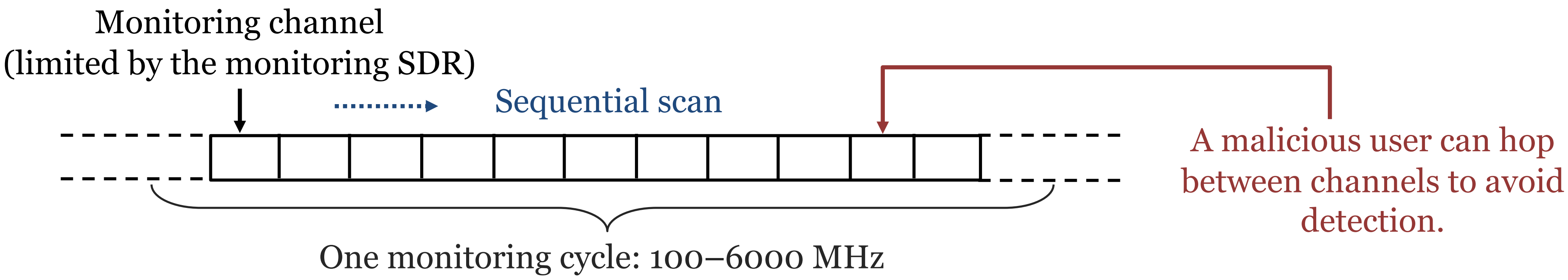
Main Takeaway:

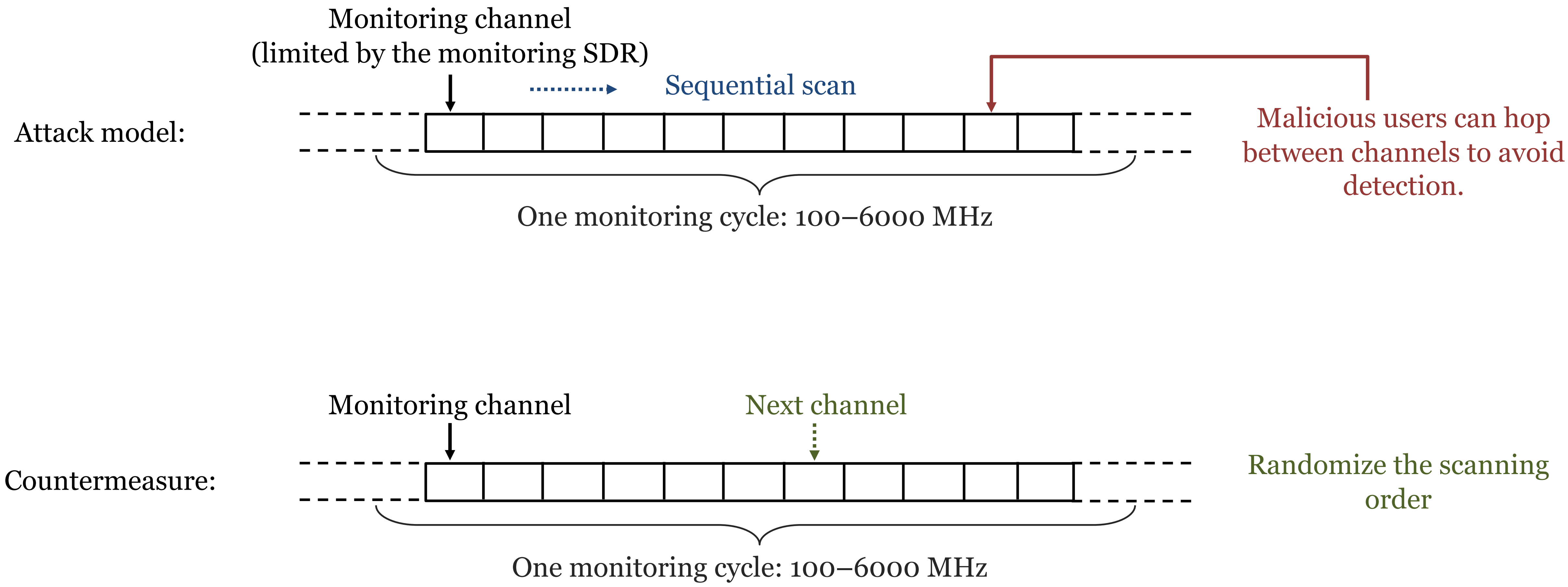
- FDMonitor shows *high alert accuracy* for spectrum monitoring.
- FDMonitor is *robust* across a variety of users, their signals, and the varying weather.
- FDMonitor ran ~1.9 million times in the 27 months. 45 false discoveries in this period correspond to a false alarm rate of approximately $2 * 10^{-5}$.

Adversarial Behavior and Countermeasure

Attack model:

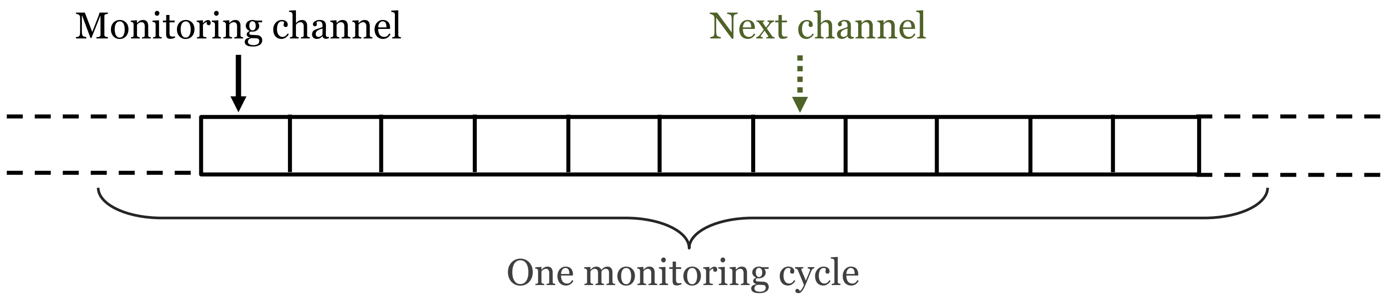


Adversarial Behavior and Countermeasure

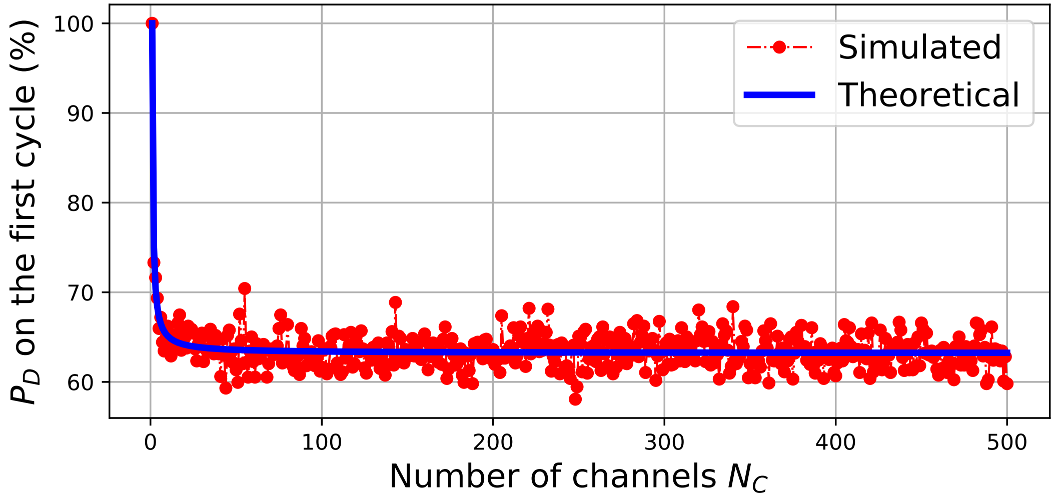


Countermeasure Performance

Countermeasure:



Randomize the scanning order



The probability of detecting violation, P_D, in the first cycle for N_C =214 (deployed FDMonitor) is 65.18%.

Summary

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- Propose FDMonitor as a systems solution that separates mixed source signals, sends spectrum violation alerts, and automatically turns off the transmitters as necessary.
- Implement FDMonitor and deploy it on 19 shared SDR platforms available to researchers on POWDER.
- Evaluate FDMonitor's separation performance thoroughly over ranges of four RF parameters: modulation type, carrier frequency, bandwidth, and transmit power.
- FDMonitor has been running continuously on POWDER since 2021. It achieves a 95% positive predictive value of all reported violations over 27 months of operation.

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THANK YOU

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