AI-Enabled Spectrum Coexistence between Active Communications and Passive Radio Services: Fundamentals, Testbed and Data

https://sites.google.com/view/swift-ai-spectrum

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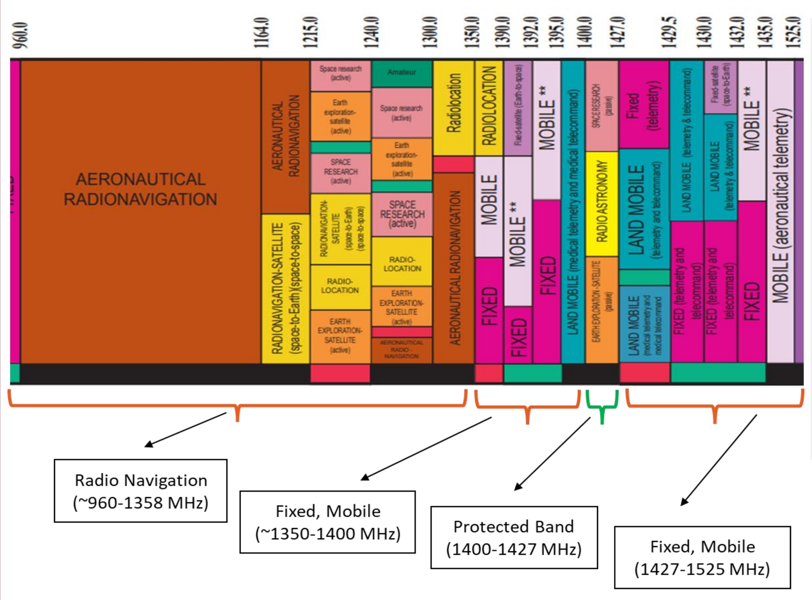
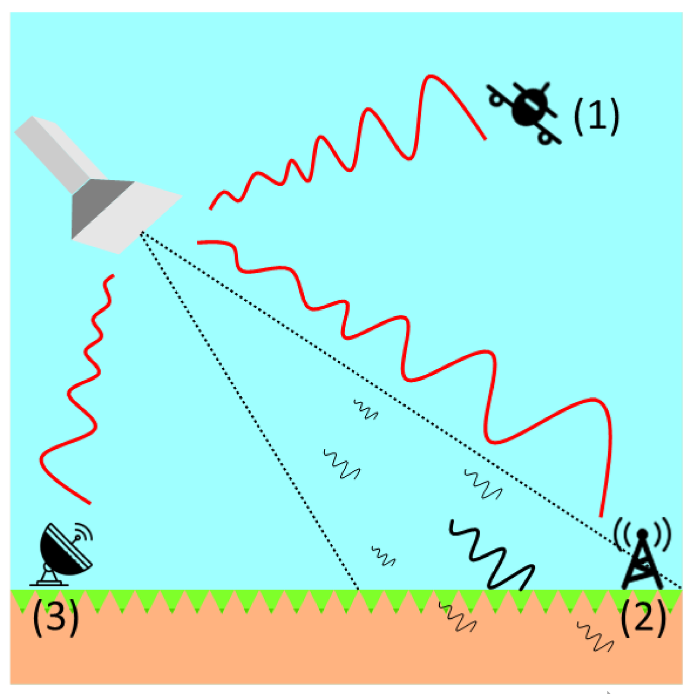
Project Overview



- Radio astronomy (RA), remote sensing (RS) and other passive sensing services are indispensable in modern society
- Active wireless technologies such as IoT, UAVs and 5G wireless networks are driving advances in key sectors such as healthcare, manufacturing, defense, and transportation

The growth of active wireless systems often increases radio frequency interference (RFI) experience by passive sensors

This needs research on active and passive spectrum coexistence



Task 1 (PHY-APP Layer)

1.1 AI-Enabled RFI detection and mitigation

1.2 Sparsity-based RFI detection and mitigation utilizing existing datasets from SMAP and UWBRAD

Task 2 (MAC-PHY Layer)

2.1 Sparse radio frames by wireless channel virtualization

2.2 Deep Reinforcement learning for channel mapping

2.3 AI-based Active transmission optimization

Task 3: Testbed

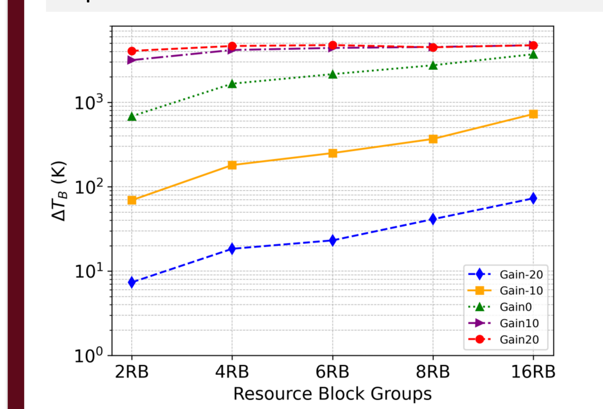
3.1 Ground and aerial system prototyping

3.2 Deployment of and installation of drone-based L-band radiometer

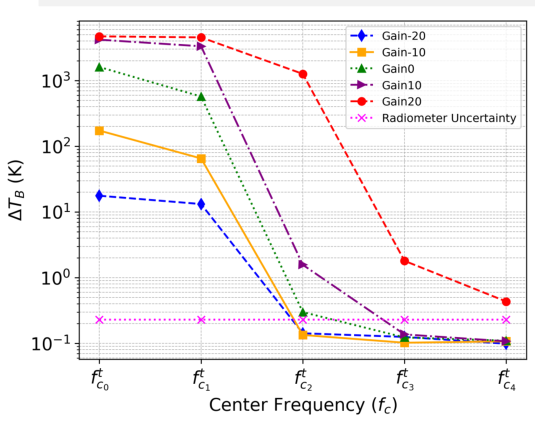
3.3 System emulator

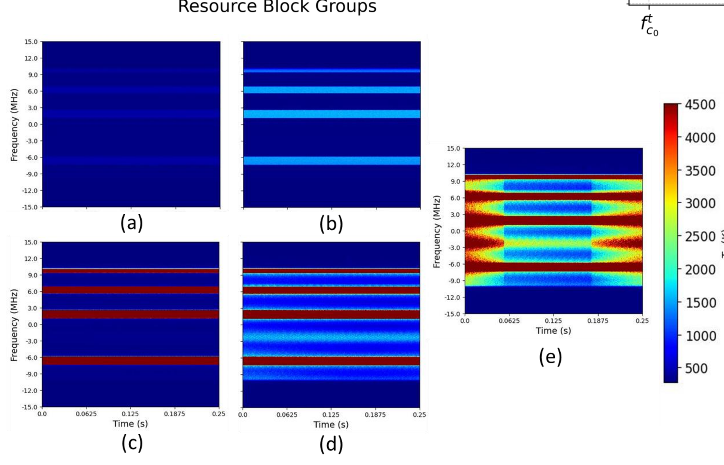
Impact of 5G Waveforms in Radiometer

Impacts of RFI (T_B) on **in-band** transmissions considering various signal gains and RBGs for H-pol

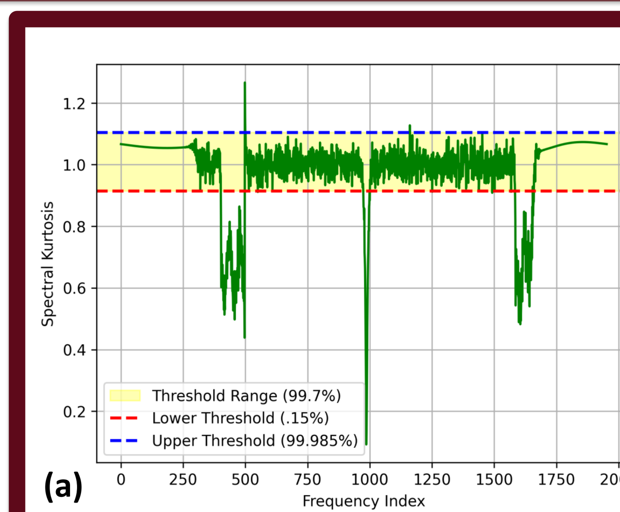


Impacts of RFI on a combination of in-band and out-of-band transmissions (**transition-band**) considering various signal gains and 4 RBGs

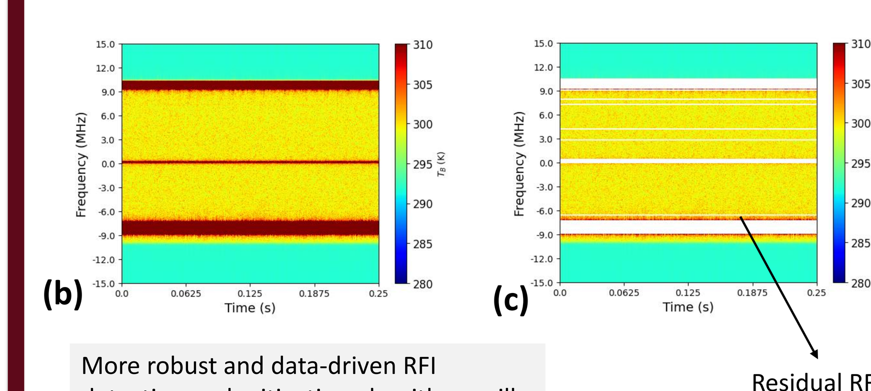




Fully calibrated high-resolution spectral T_B in radiometer with in-band transmissions considering 4 RBGs and different power levels. Recorded ground truth (no-RFI) T_B in this sample is 298.95 K



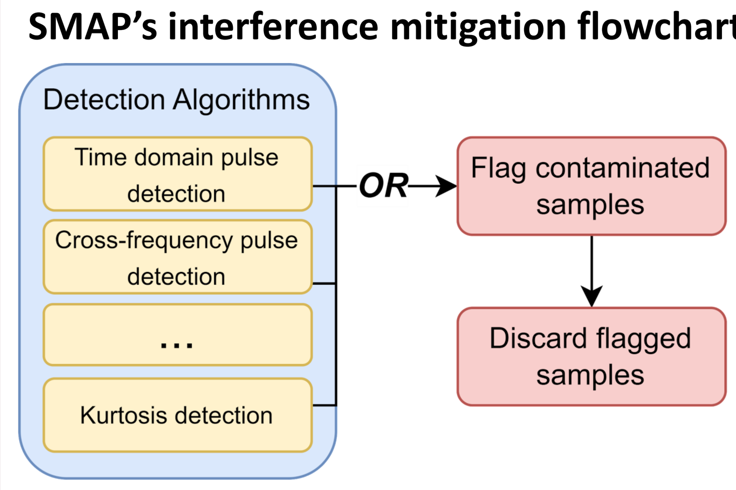
(a) **Spectral kurtosis** of RFI contaminated sample. Spectrogram (b) before and (c) after RFI removal with 2RBG and gain -10. Measured T_B after RFI removal is 297.3633 K and ground truth T_B is 296.45 K



More robust and data-driven RFI detection and mitigation algorithms will be further evaluated

Autoencoder-Based RFI Mitigation for SMAP Passive Radiometer

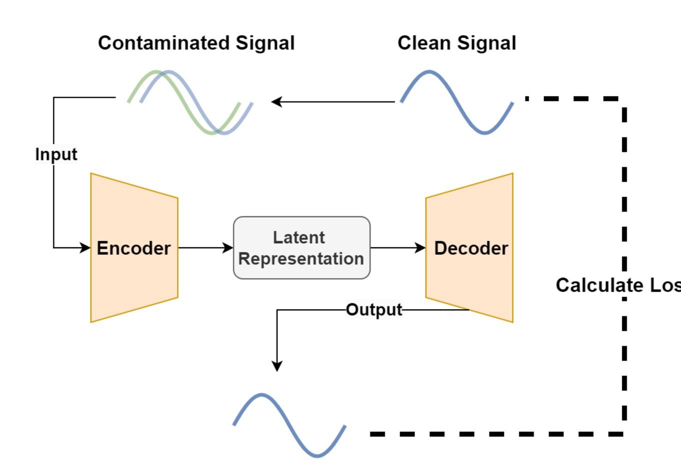
SMAP's interference mitigation flowchart

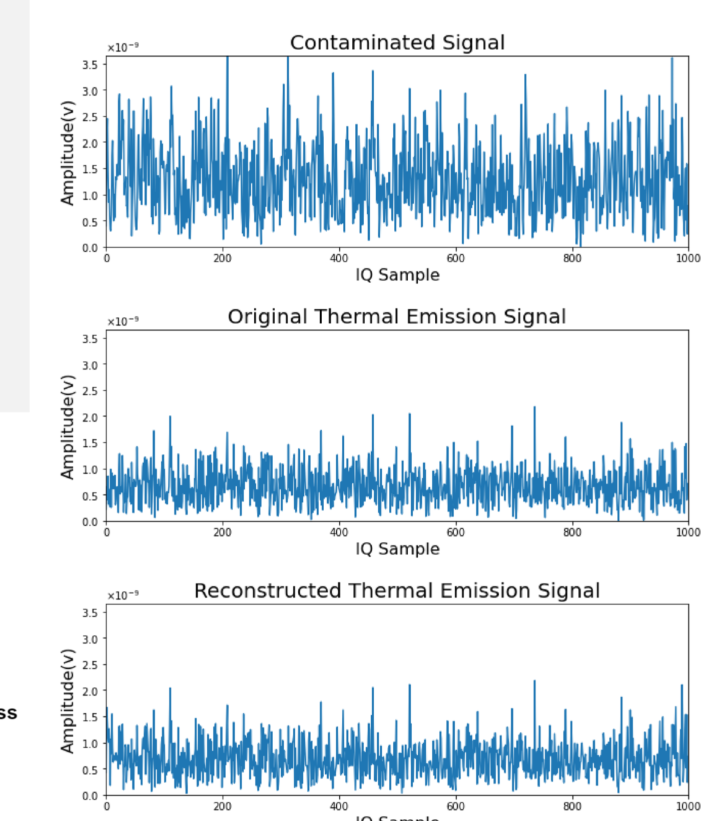


- Lost information (discarded samples)
- Too conservative
- Handcrafted parameters
- An Interference mitigation method which **reconstructs** the information from the contaminated signal instead of discarding is desired

Denoising Autoencoder (DAE) steps:

- The received contaminated signal is given as the input to the DAE
- The DAE outputs a reconstructed signal.
- The reconstructed signal is compared with the clean signal and loss is calculated
- DAE reconstructs the clean signal from the contaminated signal

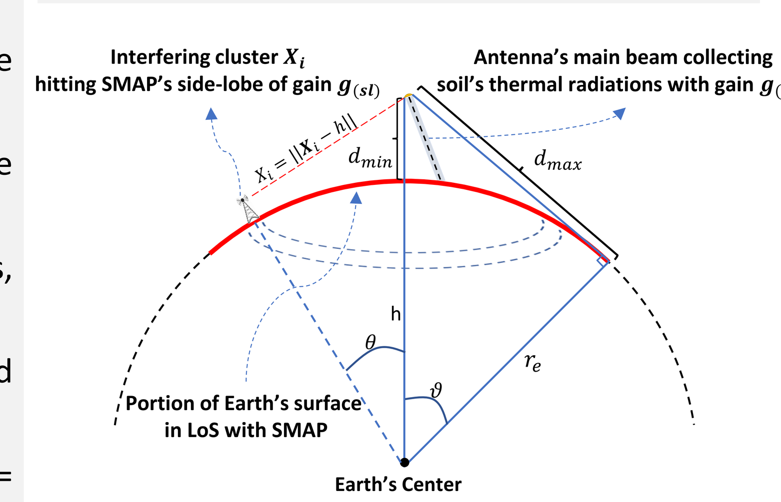


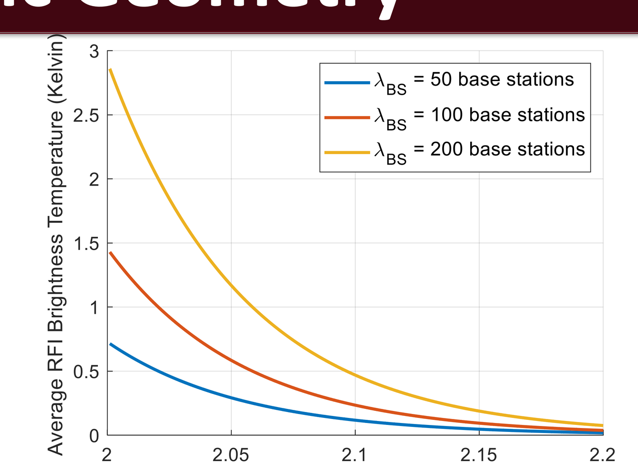


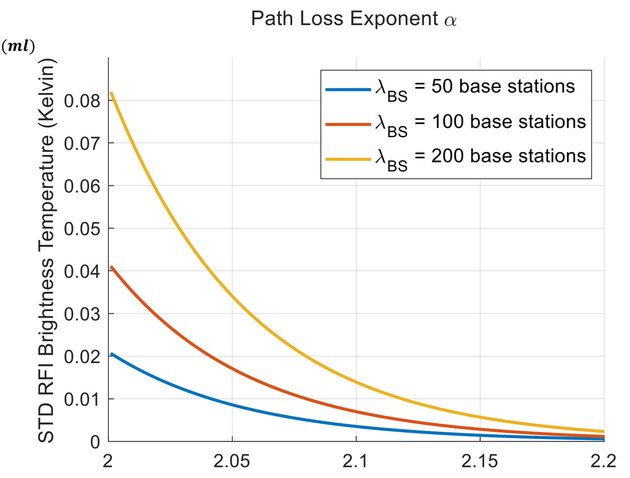
Aggregate RFI Analysis using Stochastic Geometry

- **Goal:** Model aggregate RFI induced on a space-borne passive RS satellite from a large-scale terrestrial NextG network
- Use a **Thomas Cluster Process** to model the distribution of cellular Base Stations (BSs)
  - Each cluster represents a dense urban area
- Assume all radiated power from BSs is directed at the satellite (worst-case analysis)
- Derive the **characteristic function** of aggregate RFI at the RS satellite
- Using the characteristic function, derive the **statistical properties** of the aggregate RFI
  - Cumulants, average, variance, skewness, and kurtosis.
- Analyze impact of average cluster density and number of active BSs in each cluster on the RFI
- RFI must be kept below tolerable threshold τ = 1.3 Kelvin for NASA's SMAP satellite

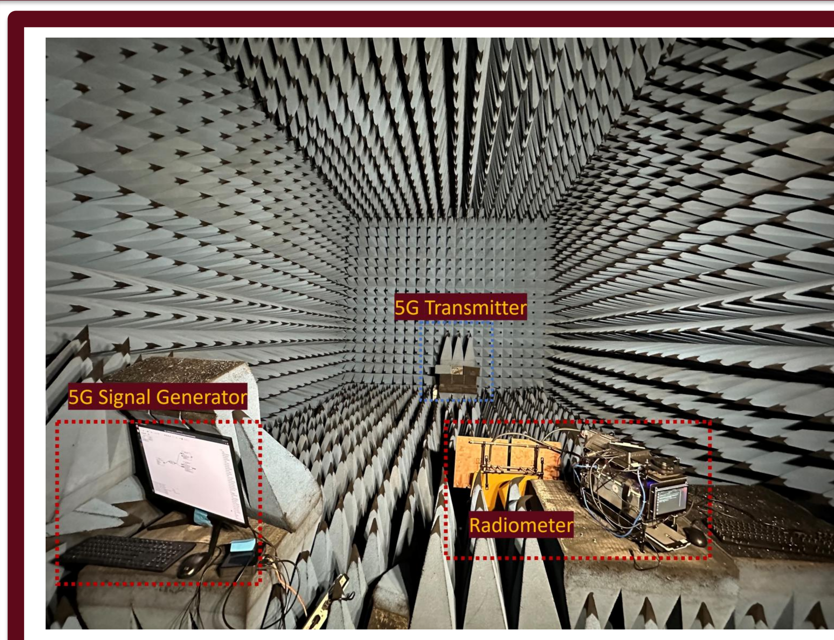
- λ_c = 1 cluster (dense urban area) every 10000 km^2. On average, 2500 clusters on Earth exposed to the satellite
- λ_{BS} = 50, 100, 200 BSs per cluster. On average, 125, 250, and 500 thousand BSs are exposed to SMAP
- $g_{(sl)} = -60$ dB (extremely low side-lobe gain of SMAP's antenna)







Testbed Preparation



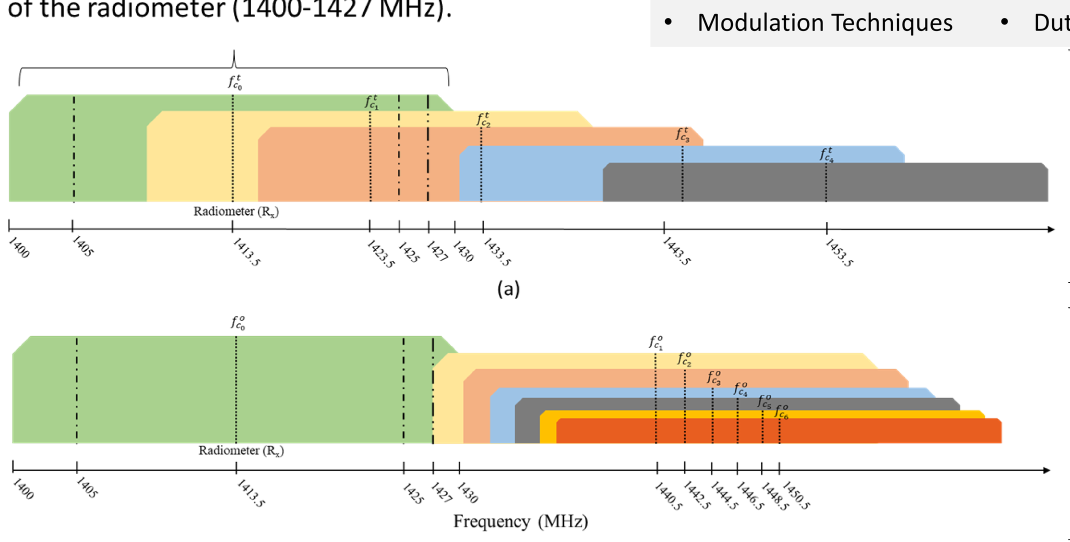
- Currently there is no publicly available dataset for active-passive co-existence research
- We have developed an open dataset and accompanying processing scripts for both **transmitted 5G samples** and **radiometer measurements**
- SDR-based digital processing unit enables acquisition of raw IQ samples at the radiometer
- A customizable 5G NR system enables transmitting various wireless communication signals

Experimental Scenario

In Band: 5G waveforms were intentionally propagated within the operational bandwidth of the radiometer (1400-1427 MHz).

Independent Variables in Experiment Campaign:

- Transmission Bands
- Power Gains
- Modulation Techniques
- Resource Block Allocations
- Duty Cycles

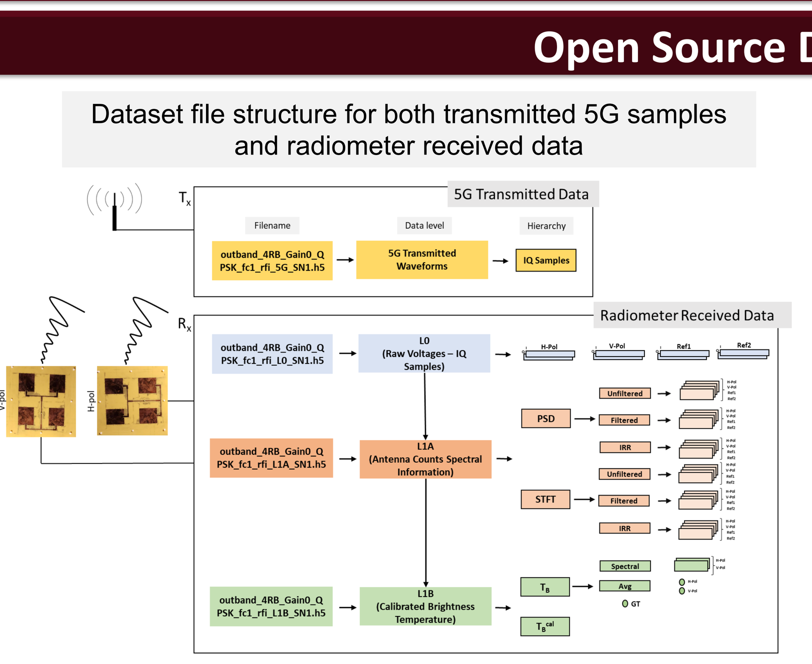


Transition Band: The center frequency of transmitted signals are shifted with 10 MHz step size spanning from 1423.5 MHz to 1453.5 MHz.

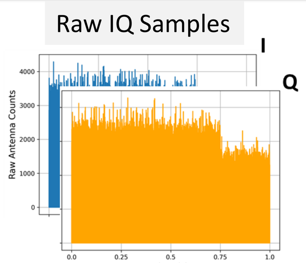
Out-Of-Band: Transmitted signals are outside the operating bandwidth of the radiometer.

Open Source Dataset

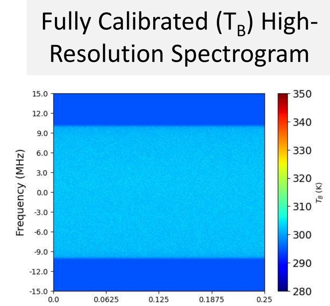
Dataset file structure for both transmitted 5G samples and radiometer received data



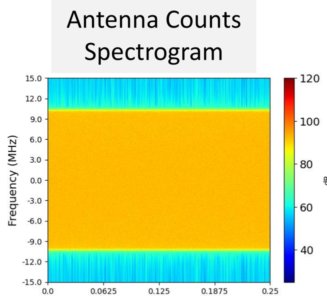
Raw IQ Samples



Fully Calibrated (T_B) High-Resolution Spectrogram



Antenna Counts Spectrogram



Dataset and Processing Scripts Available [GitHub Link]

Broader Impacts

ICC 2024 ***(Workshop – June 13, 2024)***
Spectrum Sharing Technology for Next Generation Communications
https://www.nist.gov/news-events/news/ieee-icc-2024-3rd-workshop-spectrum-sharing-technology-next-generation

4th Buffalo Day for 5G and Wireless Internet of Things (Panel – Nov. 18, 2022) **Active-Passive Spectrum Coexistence**
Moderator: Alhussein A. Abouzeid (NSF), *Panelists:* C. Chen (UVA), R. Berry (Northwestern), D. Pados (FAU), M. Kurum (MSU)

Education (Graduate Course – Fall 2022, Spring 2024)
ECE 8990 - Microwave Remote Sensing
Instructor: Mehmet Kurum

Collaborating with NASA (Research Seminar – Jan. 23, 2023)
Enabling Space Exploration by Autonomous Smart Microwave Radiometers Onboard Small Satellites
Speaker: Mehmet Ogut (NASA Jet Propulsion Laboratory)

IGARSS 2023 (Community Contributed Session– July 16, 2023)
Coexistence of Communication and Passive Sensing Technologies
Organizers: Mehmet Kurum and Ali Gurbuz

Research Experiences for Undergraduate Students (REU)
REU at MSU: Supported students: 6
CSTEP at UB: Supported students: 1 (Summer 2023 – present)

Sharing Data and Research Outcomes Through Website (Fall 2021)
https://sites.google.com/view/swift-ai-spectrum/home

List of Publications

1. A. M. Alam et al., "A Physical Testbed and Open Dataset for Passive Sensing and Wireless Communication Spectrum Coexistence," in IEEE Access, vol. 12, pp. 131522-131540, 2024, doi: 10.1109/ACCESS.2024.3453774.
2. Ahmed Manavi Alam, Md Mehedi Farhad, Walaa Al-Qwider, Ali Owfi, Mohammad Koosha, Nicholas Mastronarde, Fatemeh Afghah, Vuk Marojevic, Mehmet Kurum, Ali Gurbuz, March 31, 2024, "Dataset for Spectrum Coexistence in Passive Sensing and Wireless Communication", IEEE Dataport, doi: https://dx.doi.org/10.21227/968t-td34. **[Public Dataset]**
3. A. M. Alam, M. M. Farhad, M. Kurum and A. Gurbuz, "An Advanced Testbed for Passive/Active Coexistence Research: A Comprehensive Framework for RFI Detection, Mitigation, and Calibration," 2024 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM), Boulder, CO, USA, 2024, pp. 280-280, doi: 10.23919/USNC-URSINRSM60317.2024.10464436.
4. A. M. Alam, M. Kurum, M. Ogut and A. C. Gurbuz, "Microwave Radiometer Calibration Using Deep Learning With Reduced Reference Information and 2-D Spectral Features," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 17, pp. 748-765, 2024, doi: 10.1109/JSTARS.2023.3333268.
5. W. Al-Qwider, A. M. Alam, M. Mehedi Farhad, M. Kurum, A. C. Gurbuz and V. Marojevic, "Software Radio Testbed for 5G and L-Band Radiometer Coexistence Research," IGARSS 2023 - 2023 IEEE International Geoscience and Remote Sensing Symposium, Pasadena, CA, USA, 2023, pp. 596-599, doi: 10.1109/IGARSS52108.2023.10283002.
6. M. M. Farhad, S. Biswas, A. M. Alam, A. C. Gurbuz and M. Kurum, "SDR Based Agile Radiometer with Onboard RFI Processing on a Small UAS," IGARSS 2023 - 2023 IEEE International Geoscience and Remote Sensing Symposium, Pasadena, CA, USA, 2023, pp. 4368-4371, doi: 10.1109/IGARSS52108.2023.10282140.
7. A. M. Alam, M. Kurum, and A. C. Gurbuz, "Radio Frequency Interference Detection for SMAP Radiometer Using Convolutional Neural Networks," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 15, pp. 10099-10112, 2022.
8. A. M. Alam, A. C. Gurbuz, and M. Kurum, "SMAP Radiometer RFI Prediction with Deep Learning using Antenna Counts," *2022 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, Kuala Lumpur, Malaysia, 2022, pp. 8016-8019.
9. M. M. Farhad, A. M. Alam, S. Biswas, M. A. S. Rafi, A. C. Gurbuz and M. Kurum, "SDR-Based Dual Polarized L-Band Microwave Radiometer Operating from Small UAS Platforms," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, doi: 10.1109/JSTARS.2024.3394054.
10. Walaa H Alqwider, Ajaya Dahal, and Vuk Marojevic, "Software Radio with MATLAB Toolbox for 5G NR Waveform Generation", *Proc. IEEE DCOSS 2022 - Test and Evaluation of Programmable Networks (TEPN) 2022 workshop*, Marina Del Rey, Los Angeles, CA, US, May 2022.
11. M. Koosha and N. Mastronarde, "Opportunistic Temporal Spectrum Coexistence of Passive Radiometry and Active Wireless Networks," *2022 IEEE Western New York Image and Signal Processing Workshop (WNYISPW)*, Rochester, NY, USA, 2022, pp. 1-4.
12. M. Koosha and N. Mastronarde, "Minimizing estimation error variance using a weighted sum of samples from the soil moisture active passive (SMAP) satellite", *2023 IEEE International Geoscience and Remote Sensing Symposium*, July 2023.
13. Koosha, Mohammad, and Nicholas Mastronarde. "Spectrum Coexistence of Satellite-borne Passive Radiometry and Terrestrial Next-G Networks." *arXiv preprint arXiv:2402.08002* (2024).
14. A. Owfi, F. Afghah, and J. Ashdown, "Meta-Learning for Wireless Interference Identification", *IEEE Wireless Communications and Networking Conference (WCNC)*, 2023.
15. A. Owfi and F. Afghah, "Autoencoder-Based Radio Frequency Interference Mitigation for SMAP Passive Radiometer," IGARSS 2023 - 2023 IEEE International Geoscience and Remote Sensing Symposium, Pasadena, CA, USA, 2023, pp. 6783-6786, doi: 10.1109/IGARSS52108.2023.10281939.

Award #2030291
Award #2030047
Award #2030157

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