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Spectrum Sharing via Collaborative RFI Cancellation for Radio Astronomy

Maqsood Careem, Shuvam Chakraborty, Aveek Dutta, Dola Saha
Mobile **E**merging **S**ystems & **A**pplications (MESA) Lab
Department of Electrical & Computer Engineering
University at Albany, SUNY

Gregory Hellbourg
Department of Astronomy
California Institute of Technology

UNIVERSITY AT ALBANY
State University of New York

MESA

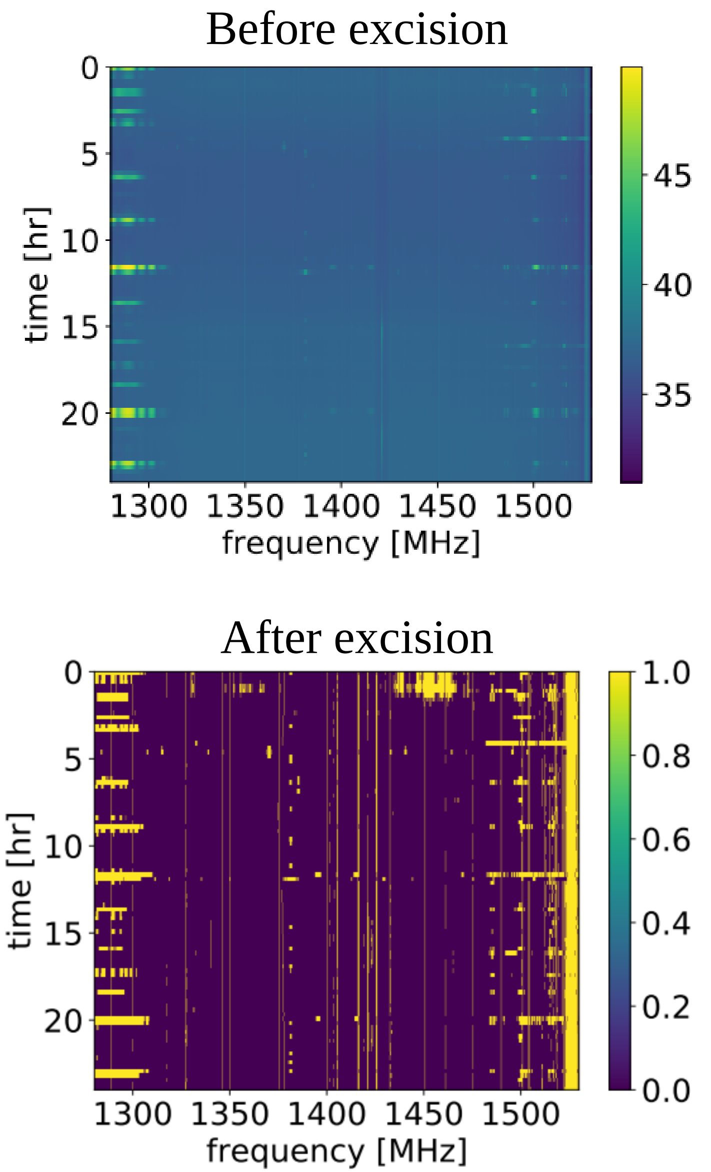
CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Motivation

RFI Mitigation (active)

Methods in practice
- Strong attenuation of known fixed sources
- Statistical analysis to flag and discard RFI corrupted data (**excision**)

Issues
- Unable adapt to changing statistics of RFI
- Time-frequency resource is underutilized[2]
- Reduces sensitivity of the telescope
- High probability of loss of signal of interest
- Radio telescopes highly sensitive to RFI.

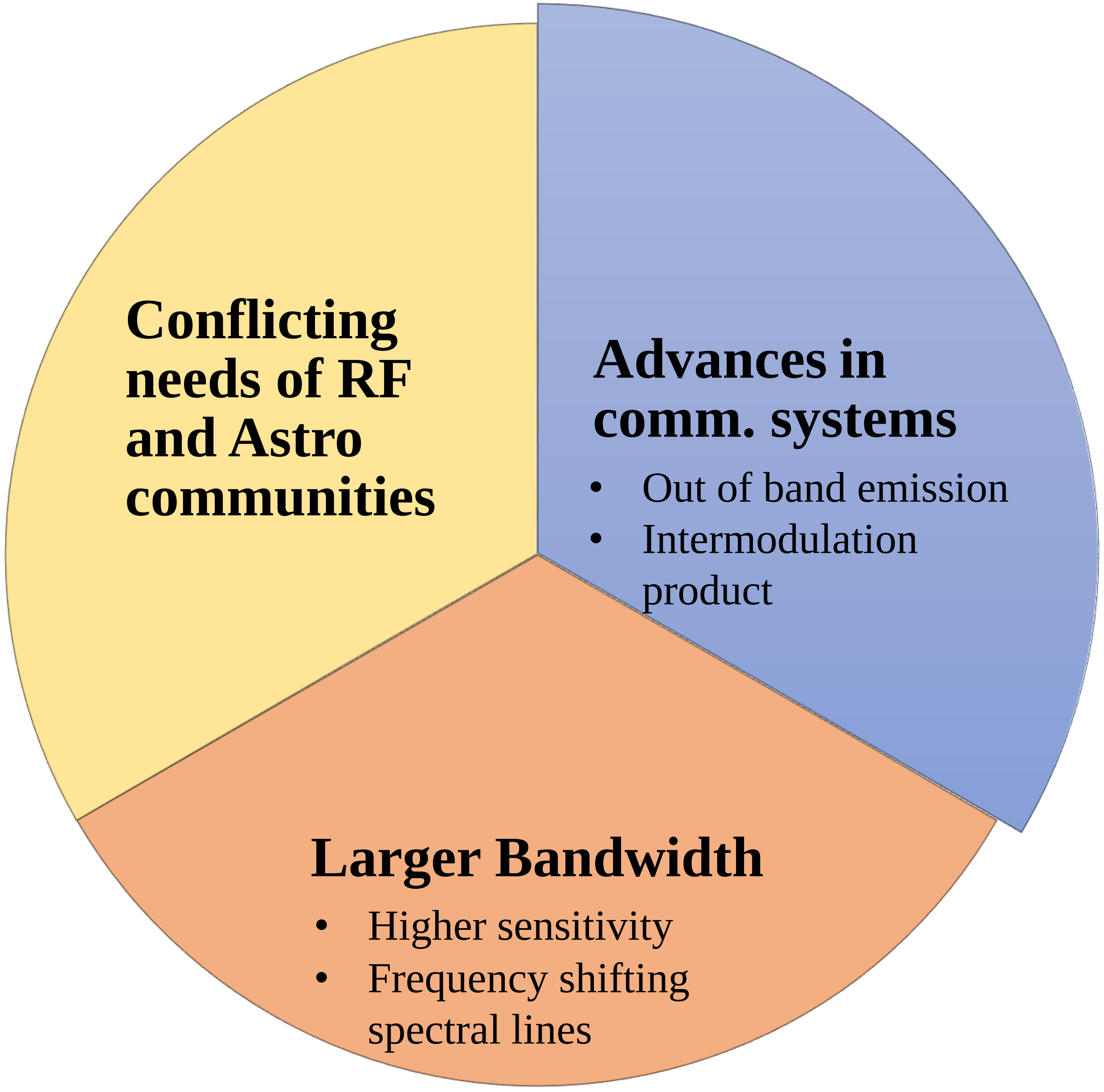


RFI flagging and excision[1] (including H1 line)

[1] Obtained from Deep Synoptic Array (DSA-110) at OVRO
[2] Tuned to minimize non-detection resulting in significant data loss

Contribution

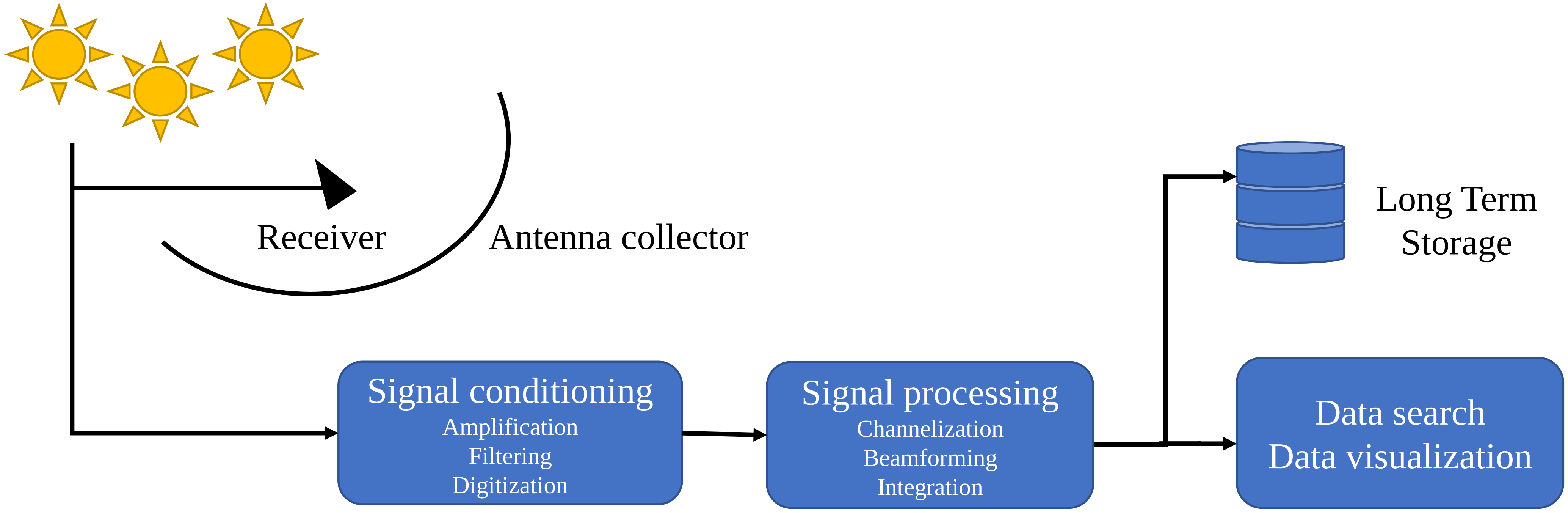
- We propose a **collaborative RFI mitigation** method that **reduces excision by 89.04 %**
- We **characterize the RFI at its source** (base station for LTE) using Eigen-decomposition
- We exploit the **shared statistical properties** of the signal to **nullify the effect of RFI** and **reuse** the reconstructed space signal.



Why collaborative apparatus ?

Signal Models

Acquisition of Astronomical Signals at Telescope



Telescope parameters	Signal duration (s)	Number of antennas in DSA-110	Coarse channel width (MHz)	Fine channel width (kHz)	Signal of Interest	Location in spectra (MHz)
Values	4	25 (time of capture)	11.7	30.5	Hydrogen (H1) line	1420

Telescope Signal Model

RFI contribution

$$x_{f_c}[n] = x_A[n] + x_N[n] + x_R[n] \approx x_N[n] + x_R[n]$$

$x_{f_c}[n] \sim \mathcal{NC}(x_R[n], \sigma^2)$

Channelized baseband signal at center frequency f_c at time sample n

$x_A[n] \sim \mathcal{NC}(0, \sigma_A^2)$

Contribution of astronomical sources in telescope field of view

$x_N[n] \sim \mathcal{NC}(0, \sigma_N^2)$

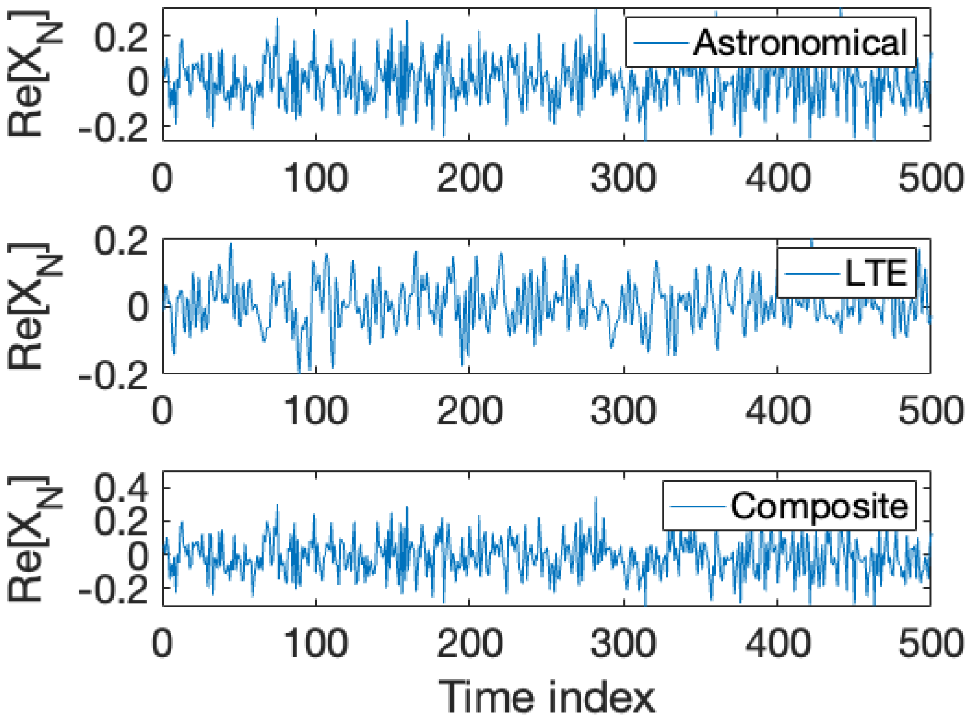
System noise contribution

Collaborative RFI Cancellation

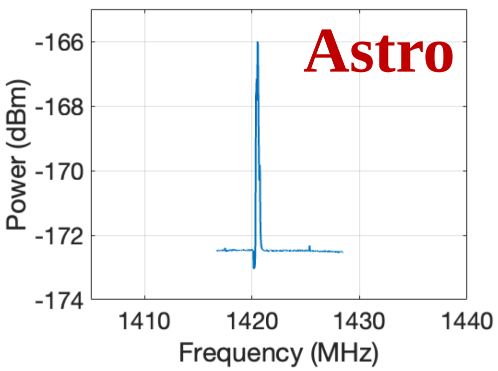
Temporal & Spectral Characteristics

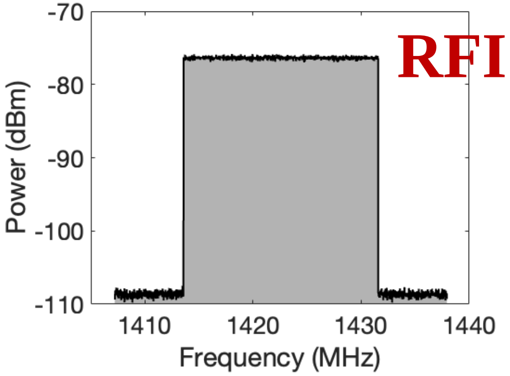
Signals in time-domain

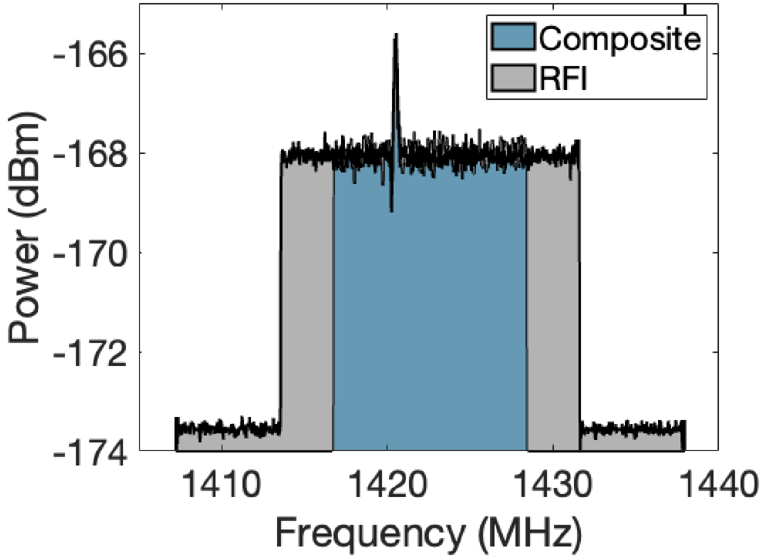
- Astronomical Signal - H1 line at 1420 MHz
- RFI – LTE signals served by a BS



Composite Signal Spectrum







A. Eigenspace-based Characterization

Characterization:

- RFI at BS
- Composite sig at telescope

Karhunen-Loeve Transform: KLT

- Applicable to any signal type
- Decomp into adaptive basis
- Detects weak signals
- Optimal in MMSE sense

Implemented using Singular Spectral Analysis for practicality.

Characterization

1. Input sample sequence

$$\mathbf{x} = [x_0, x_1, x_3, \ldots, x_N]^T$$

2. (L x K = N-L+1) Hankel matrix

$$\mathbf{U} = \begin{bmatrix} x_0 & x_1 & x_2 & \cdots & x_K \\ x_1 & x_2 & & & \vdots \\ x_2 & & & & \vdots \\ \vdots & & & & x_{K+L-3} \\ \vdots & & & x_{K+L-3} & x_{K+L-2} \\ x_L & \cdots & \cdots & x_{K+L-2} & x_{K+L-1} \end{bmatrix}$$

3. Covariance matrix

$$\mathbf{R}_{xx} = \mathbb{E}[\mathbf{U}\mathbf{U}^H]$$

4. Eigen-decomposition

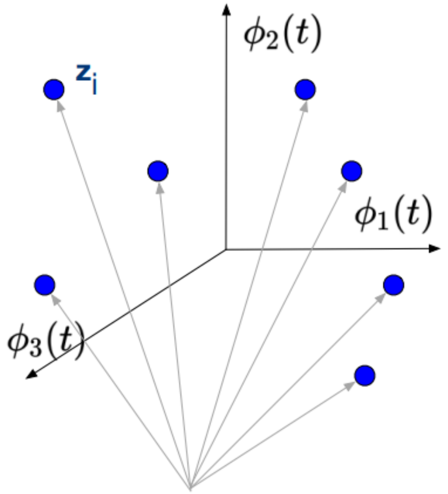
$$\mathbf{R}_{xx} = \mathbf{\Phi}\Lambda\mathbf{\Phi}^H$$

$$\Lambda = \mathrm{diag}\{\lambda_0, \lambda_1, \ldots, \lambda_M\}$$

Reconstruction

5. SSA implementation of KLT

$$\mathbf{z}_i = \mathbf{\Phi}^H \mathbf{x}_i$$



Time series **x** projected on to orthogonal Eigenfunctions

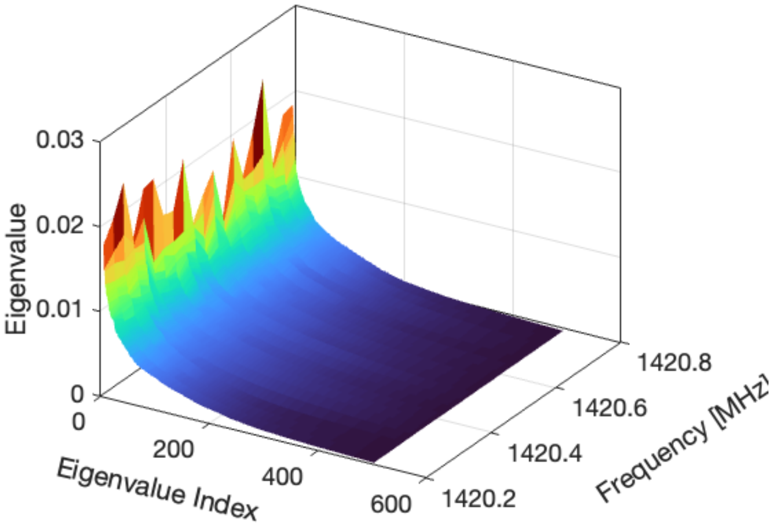
6. Inverse- SSA (Inverse-KLT)

$$\hat{\mathbf{x}} = \mathrm{DiagonalAverage}(\mathbf{\Phi}\mathbf{z})$$

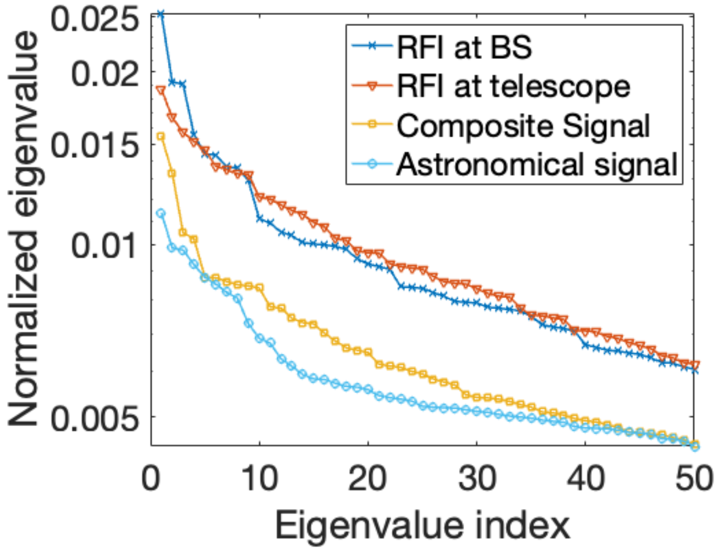
Eigenspectra at Base Station & Telescope

Characterization at:

- Base Station:
  - RFI + Noise
  - RFI kernel: $\mathbf{\Phi}_R$
  - Shared with telescope
- Telescope:
  - Astro sig + RFI + Noise
  - Astronomical Kernel: $\mathbf{\Phi}_T$
  - Used to cancel RFI



Composite signal at telescope



Eigenvalue comparison

B. RFI cancellation with eigenspace projection

Orthogonal projector for RFI

- Using $\mathbf{\Phi}_R$ shared by BS:

$$\mathbf{P}^{\perp}_{\mathbf{\Phi}_R} = \mathbf{I} - \mathbf{\Phi}_R \left(\mathbf{\Phi}_R^H \mathbf{\Phi}_R \right)^{-1} \mathbf{\Phi}_R^H$$

$$\mathbf{P}^{\perp}_{\mathbf{\Phi}_R} x_R[n] = 0$$

- Nullifies RFI in composite signal.
- *Does not assume separability of RFI and Astro signals.*

RFI cancellation at telescope

1. Projection of eigenspace at telescope:

$$\widehat{\mathbf{\Phi}}_T = \mathbf{P}^{\perp}_{\mathbf{\Phi}_R} \mathbf{\Phi}_T$$

   - Subspace-based removal of RFI

2. Reconstruction using Inverse-KLT:
   - Hankel Matrix:

$$\widehat{\mathbf{U}}_T = \widehat{\mathbf{\Phi}}_T \mathbf{z}_T$$

   - Astronomical Signal:

$$\hat{x}_T[n] = \frac{1}{a} \sum_{k=b}^{c} \hat{\mathbf{U}}_T^{(k, n-k+1)}$$

a, *b*, *c* depend on the sample index *n*

RQF: Reconstruction Quality Factor

- Measures the combined accuracy of KLT decomposition and eigenspace-based cancellation of RFI.

$$\text{RQF} = \frac{\text{RFI-Free Power}}{\text{RFI Power}} = \frac{\left\| x_N \right\|^2}{\left\| x_T - \hat{x}_T \right\|^2} = \frac{\left\| x_N \right\|^2}{\left\| \epsilon_r \right\|^2}$$

$$\epsilon_r[n] \sim \mathcal{NC}(0, \sigma_{\text{est}}^2)$$

cumulative estimation and reconstruction error

- Derivation of the average RQF

$$\mathbb{E}\{\text{RQF}\} = \boxed{\frac{\sigma_N^2}{\sigma_{\text{est}}^2}} \left(1 + 2\frac{N-1}{N^2}\right)$$

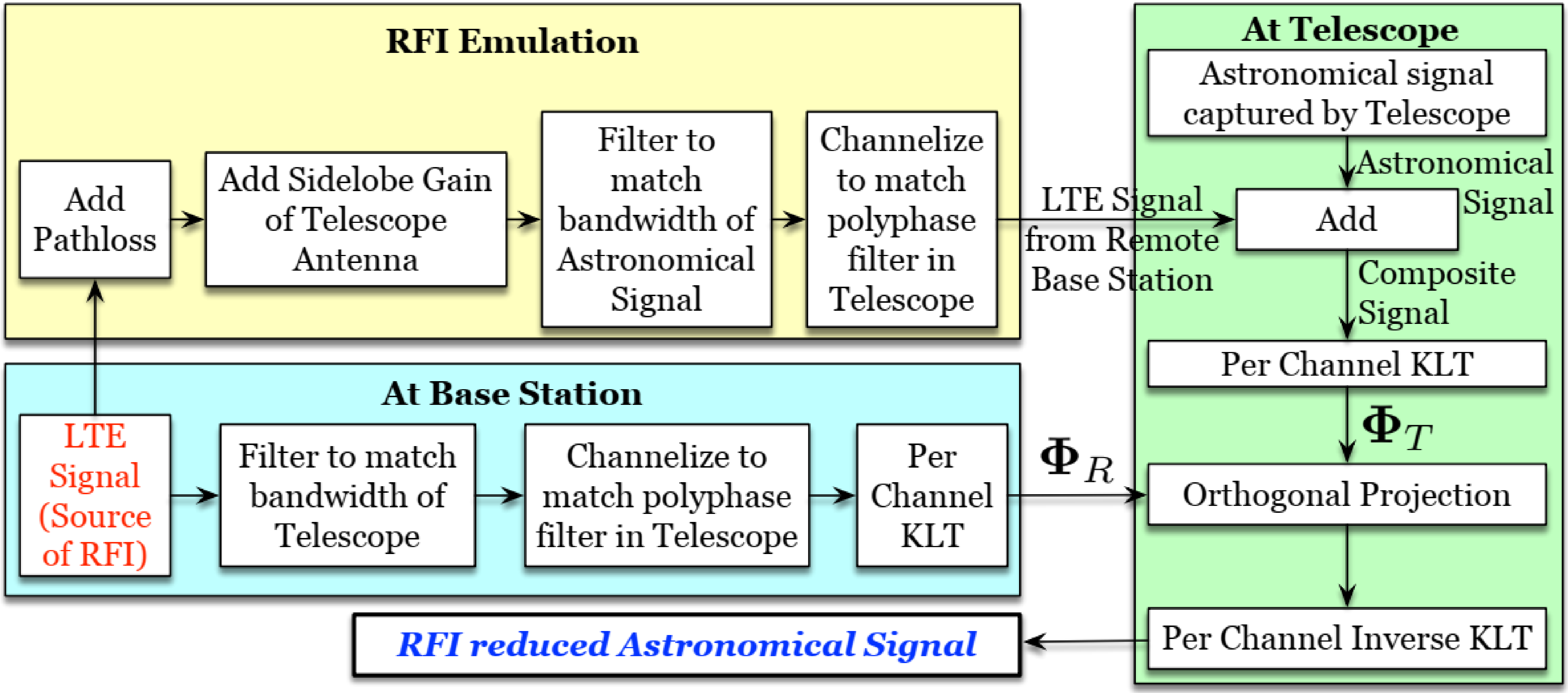
>10 else is detrimental to radio astronomy [1] → Lower bound RQF_{ref}

Number of samples in signal under evaluation

[1] "Protection criteria used for radio astronomical measurements", International Telecommunication Union (ITU)

Experiments

System Simulation for Validation of RFI Mitigation Apparatus



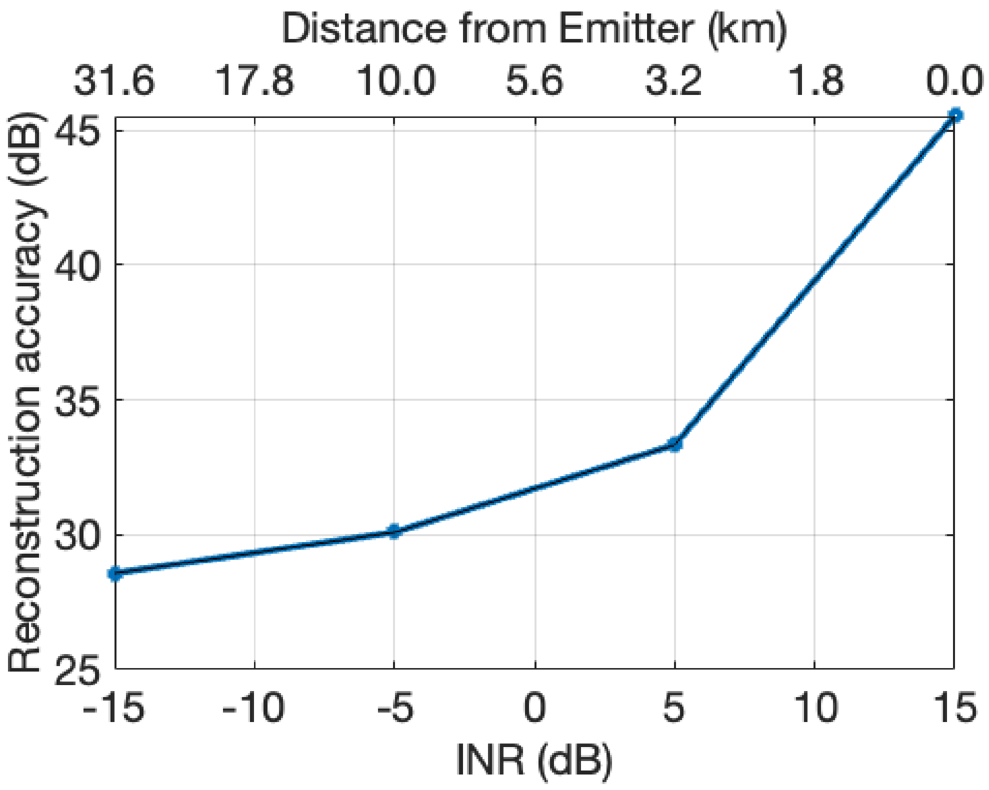
Parameters for RFI Simulation

Bandwidth (MHz)*	20
Occupied Bandwidth (MHz)*	18.015
Frame duration (ms)*	10
Subframe duration (ms)*	1
FFT length*	2048
Guard length*	847
Number of Resource Blocks*	100
Number of Frames [1]	400

*From 3GPP standardization.
[1]To match astronomical signal duration.

Results

Reconstruction Accuracy of a Sample Signal over INR



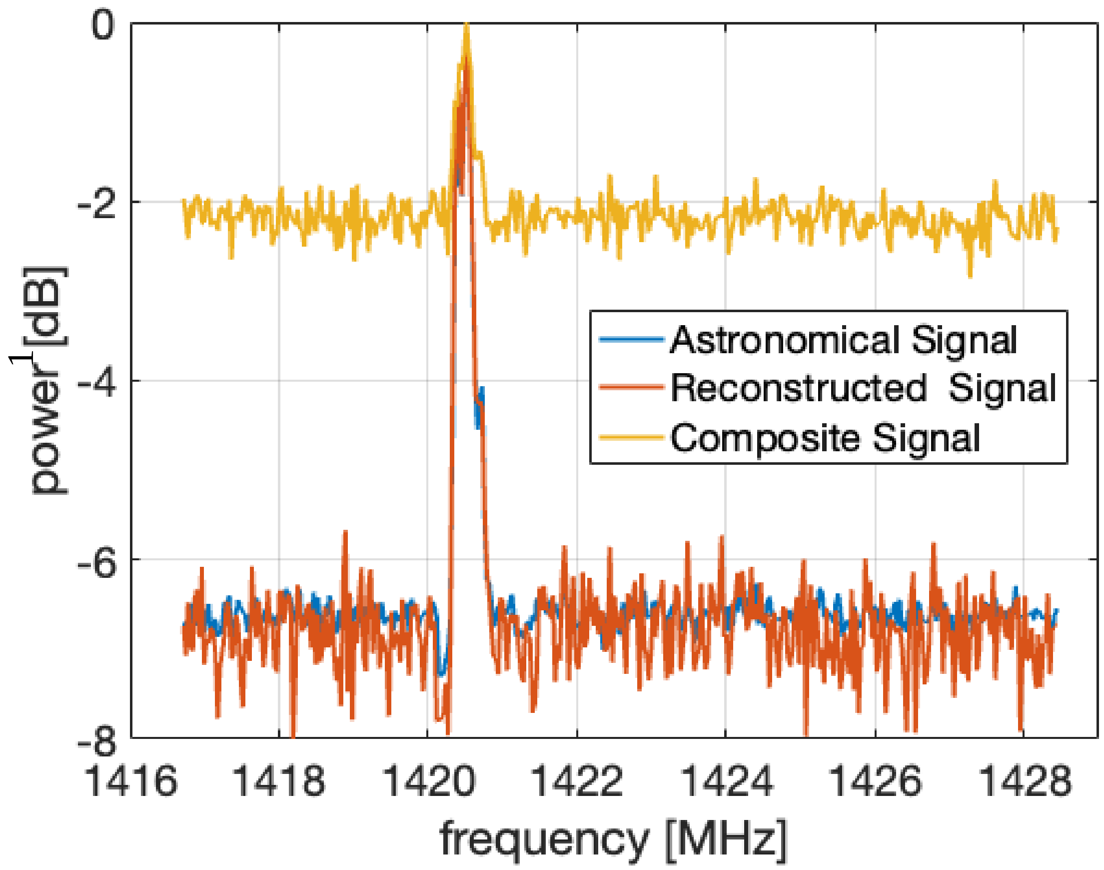
Performed on a sample of the LTE signal

Reconstruction accuracy : $20 \log_{10} \left(\frac{\|x_R\|}{\|x_R - \hat{x}_R\|} \right)$

x_R : True signal

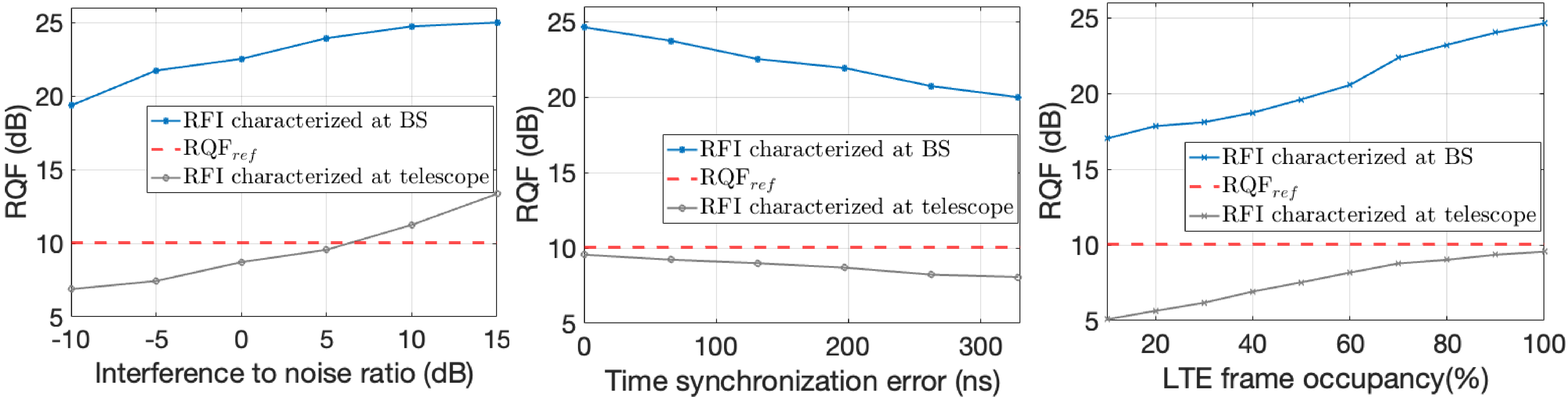
$\hat{x}_R$: Reconstructed signal

Reconstructed Signal Compared to True Astronomical Signal



[1] Power levels are relative to noise floor (-174 dBm) indicating the baseline

RQF Variation across Parameter Space of RFI[1]



[1]The parameters for reconstructed signal in previous slide: INR (**5 dB**), Time sync error (**0 ns**), Frame occupancy (**100%**)

Discussion

1. This work proposes sharing stochastic characterization of the RFI at its source, the cellular base station, with the telescope to cancel the incident RFI
2. This approach promotes collaborative spectrum sharing between the active and passive users of the spectrum
3. This method is deployable on current radio telescope
4. Managing computation cost remains a challenge due to the large eigenvalue problem
5. latency in collaboration can potentially be avoided using reference antenna at the observatory

Thank You!

Questions and feedback

(schakraborty@albany.edu, mabdulcareem@albany.edu)

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