Unsupervised Frequency Clustering for Null Space Estimation in Wideband Spectrum Sharing Networks

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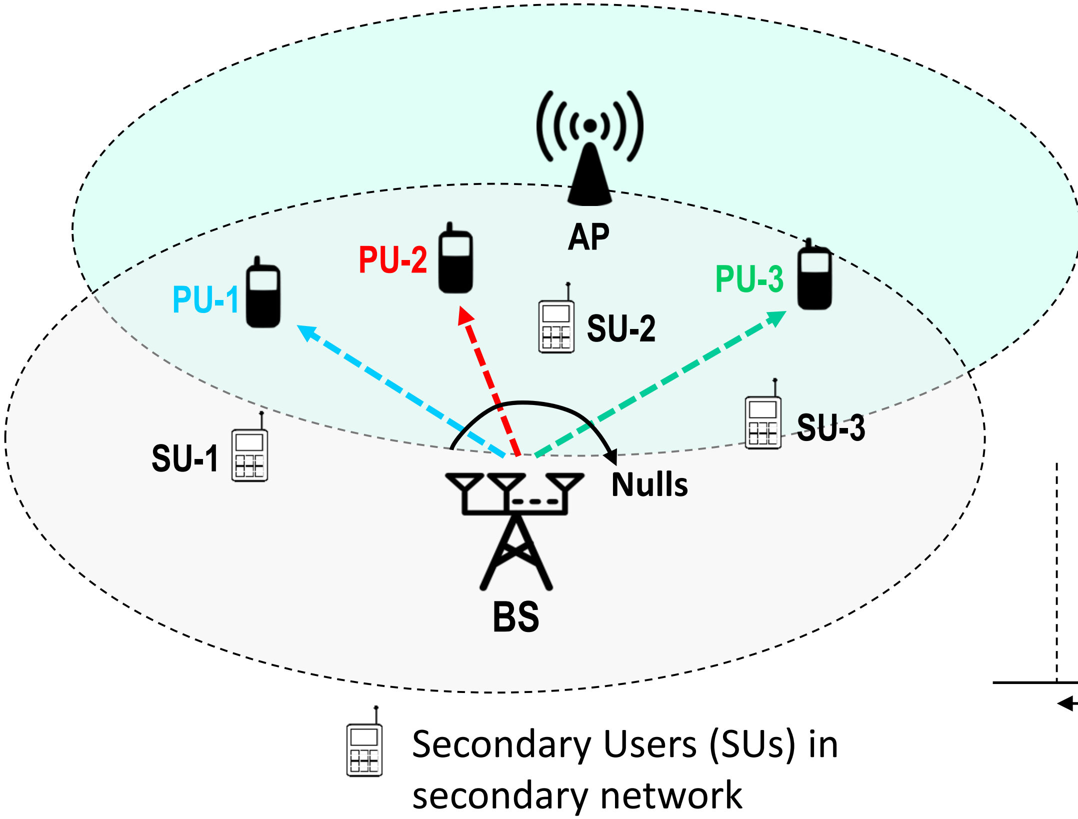
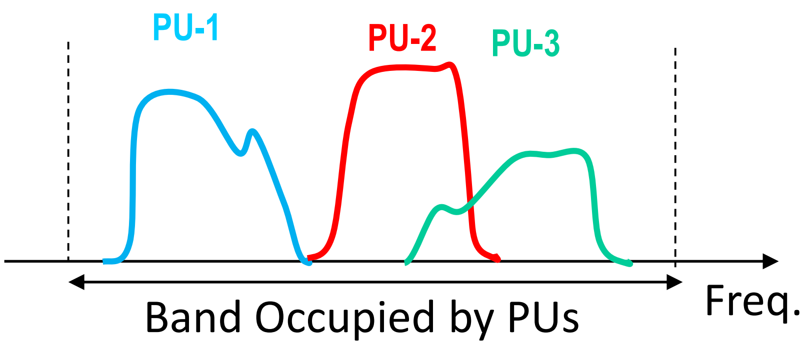
Outline

- **Introduction**
  - Wideband Null Steering for Interference Control in Spectrum Sharing Networks.
- **System Model and Proposed Algorithm**
  - Clustering of Correlated Frequency Bins for Low Complexity Null Steering
- **Numerical Results**
- **Conclusion**

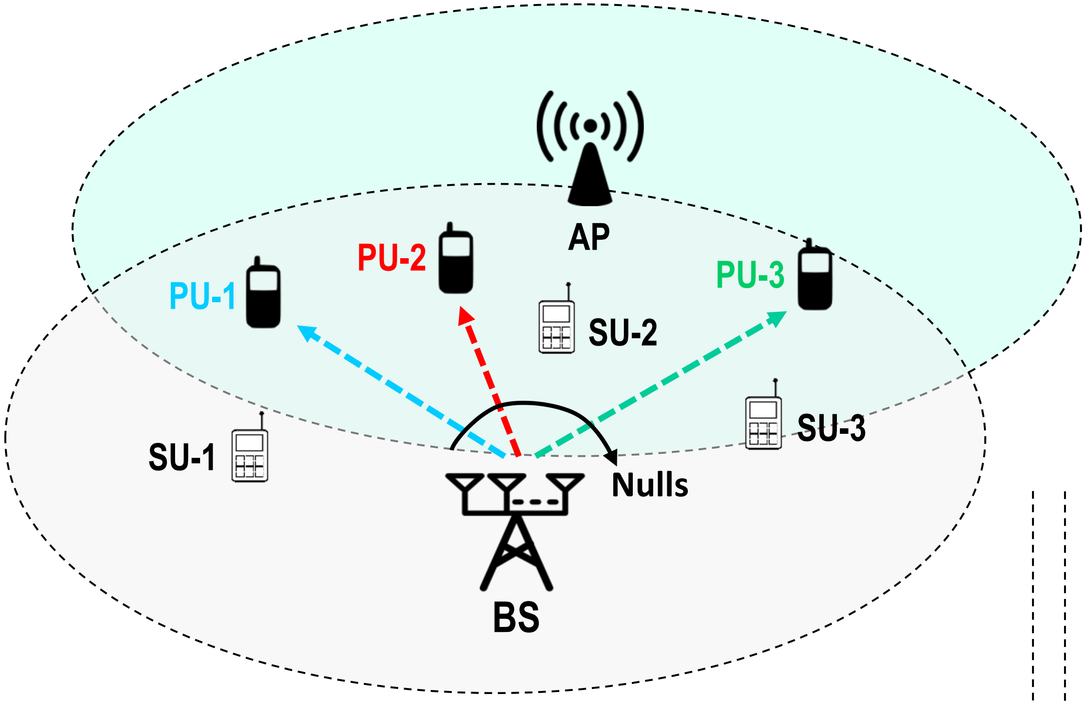
Underlay Spectrum Sharing Networks

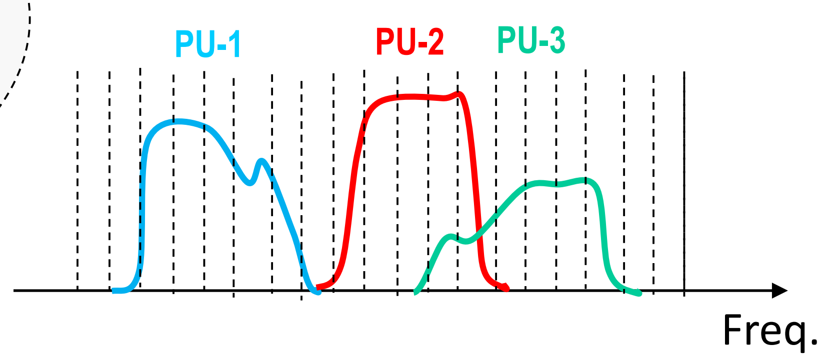




- Primary Network has existing primary users (PUs) in wideband.
- Secondary network is deployed in same band.
  - BS needs to eliminate downlink interference to PUs.
  - Use multiple antenna array to steer nulls toward PUs.

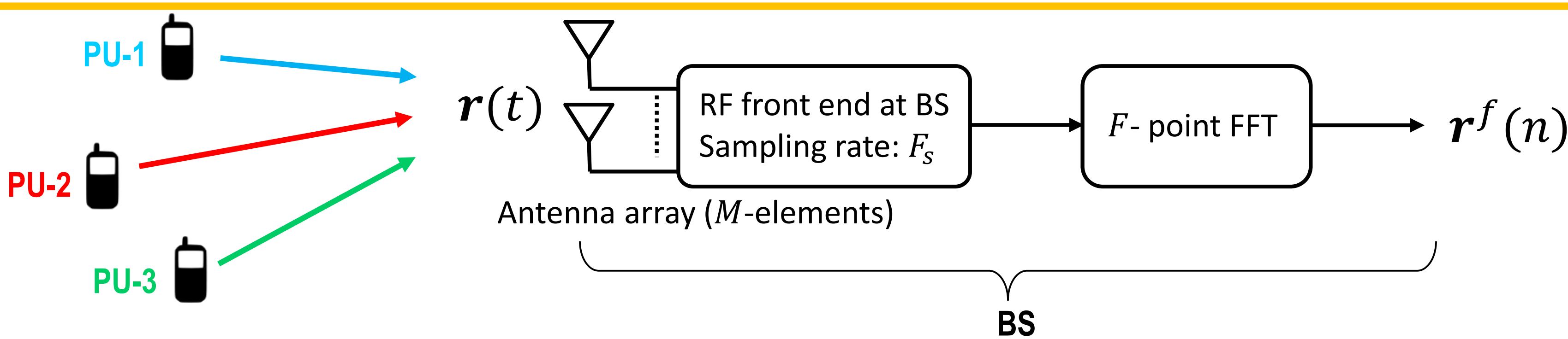
Wideband Null Steering





- Wideband null steering is required from BS, since each PU occupies wideband.
- BS uses signal received from PUs for null steering.

System Model and Problem Statement



- $\boldsymbol{r}^f(n)$: $M \times 1$ received signal vector in bin $f \in \{1, 2, \dots, F\}$ at instant $n = 0, 1, \dots, T-1$.
- $\boldsymbol{r}^f(n) = \sum_{l=1}^{L_f} \sqrt{p_l^f}\, x_l^f(n)\, \boldsymbol{h}_l^f + \boldsymbol{w}^f(n)$

L_f = number of PUs in bin f
p_l^f = transmitted power from PU-l
$x_l^f(n)$ = transmitted symbol from PU-l
$\boldsymbol{w}^f(n)$: noise vector $\sim CN\left(0, \boldsymbol{R}_w^f\right)$
$\boldsymbol{h}_l^f$ = $M \times 1$ channel vector between PU-l and BS in bin f

Problem Statement:

Estimate null space matrices $\boldsymbol{U}^f$ without prior knowledge of $\boldsymbol{h}_l^f$, such that

$$(\boldsymbol{U}^f)^H \boldsymbol{h}_l^f = \boldsymbol{0}, \forall l$$

Complexity of Existing Wideband Approach

- Existing solutions use narrowband techniques with fine frequency resolution [1,2].
- Fine frequency resolution at BS:
  - To obtain spectrum occupancy with high accuracy [3].
  - Due to overdesigned system, e.g., Δf in LTE $<$ coherence BW of extended pedestrian A (EPA) model.
  - Results in large number of bins.
  - Increases complexity.
- Complexity $\propto$ # occupied bins by PUs.
- **Proposed approach:**
  - **Exploit correlation in adjacent bins to reduce complexity.**

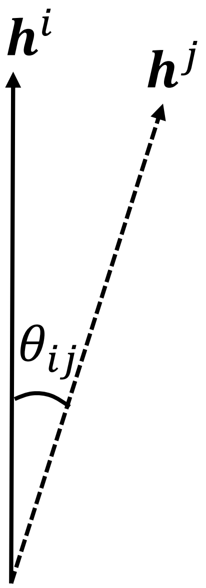
[1] Tsinos et. al., "Blind Opportunistic Interference Alignment in MIMO Cognitive Radio Systems," Emerg. Sel. Top. Circuits Syst. IEEE J. On, vol. 3, no. 4, pp. 626–639, Dec. 2013.

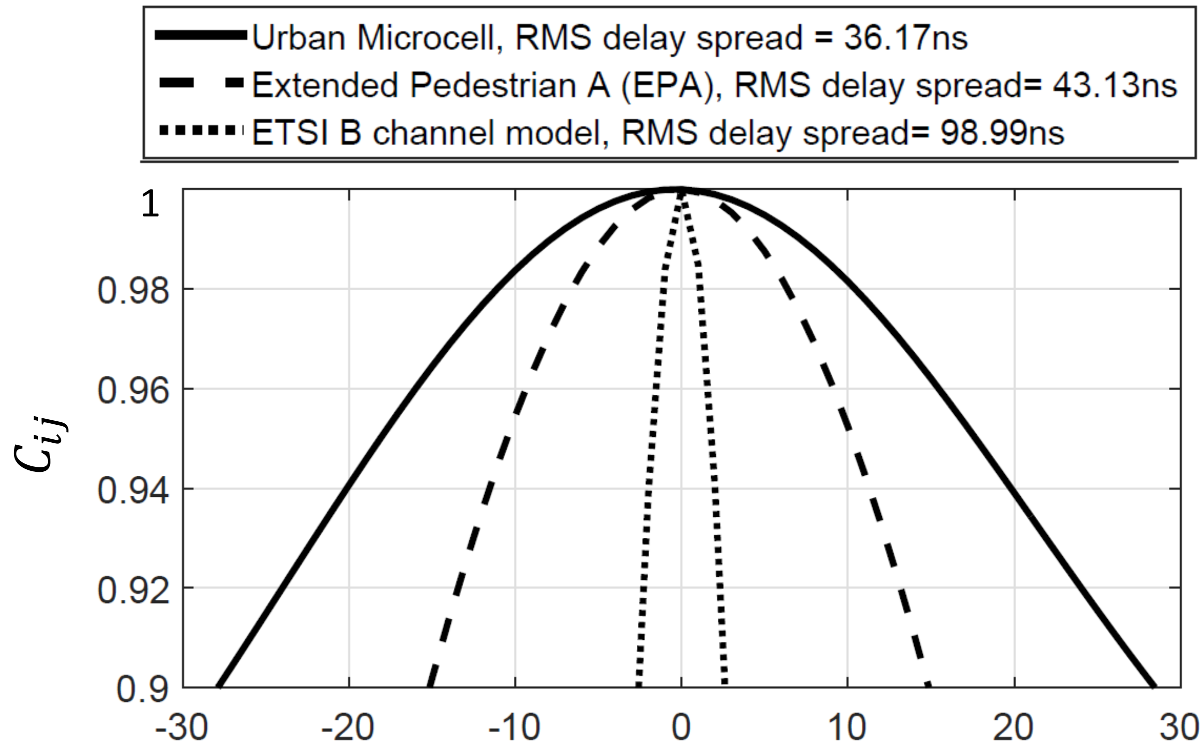
[2] Kouassi et. al. "Reciprocity-based cognitive transmissions using a MU MIMO approach," IEEE ICC, June 2013

[3] Harjani *et al.*, "Wideband blind signal classification on a battery budget," in *IEEE Commu. Magazine*,, October 2015.

Correlation vs Frequency Separation

- Correlation in channel vectors in bin i and bin j = $C_{ij} = \cos^2(\theta_{ij})$ [4]





$\boldsymbol{h}^i$: Channel vector in bin i

$\boldsymbol{h}^j$: Channel vector in bin j

Frequency bin separation $i - j$

$F_s = 20$ MHz, $F = 512$, $M = 8$.

[4] Choi et. al., "Interpolation based transmit beamforming for MIMO-OFDM with limited feedback," IEEE TSP, Nov. 2005

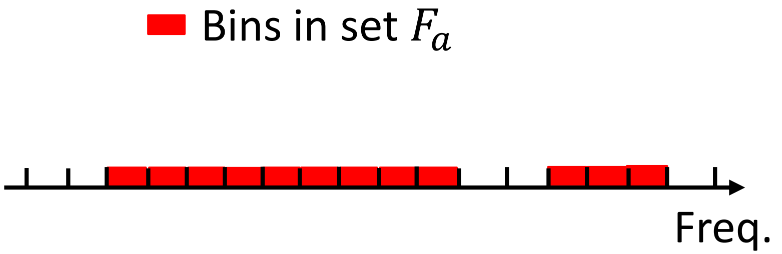
Proposed Algorithm

$\boldsymbol{r}^f(n), f \in F_a$: set of bins with at least one PU

↓

Estimate covariance matrices $\widehat{\boldsymbol{R}}^f, f \in F_a$ using T samples of $\boldsymbol{r}^f(n), n = 1, \ldots, T$

↓



Proposed Algorithm

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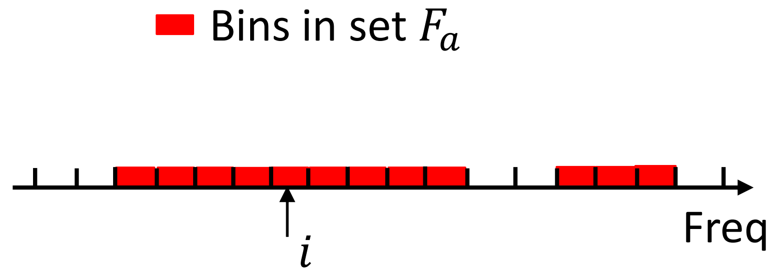
Estimate covariance matrices $\widehat{\boldsymbol{R}}^f, f \in F_a$ using T samples of $\boldsymbol{r}^f(n), n = 1, \ldots, T$

↓

$i \leftarrow$ Center bin of new cluster.
Compute null space $\boldsymbol{U}^i$ at bin i

↓

EVD of $\widehat{\boldsymbol{R}}^i - \boldsymbol{R}_w^i$
$\boldsymbol{R}_w^i$: noise covariance



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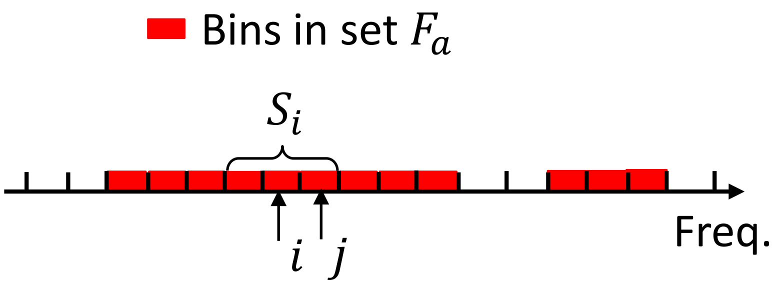
EVD of $\widehat{\boldsymbol{R}}^i - \boldsymbol{R}_w^i$
$\boldsymbol{R}_w^i$: noise covariance

↓

Form cluster S_i around bin i.
$S_i \leftarrow j$? Where $j = i \pm 1, i \pm 2, ..$

Proposed test for clustering correlated bins (?)

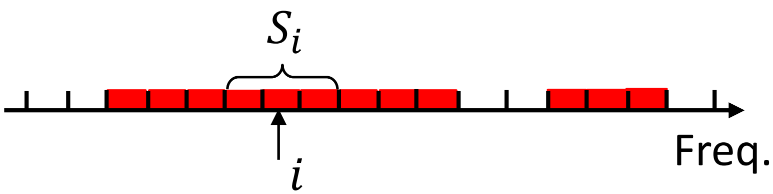
↓



Proposed Algorithm

$\boldsymbol{r}^f(n), f \in F_a$: set of bins with at least one PU

Bins in set F_a



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Form cluster S_i around bin i.
$S_i \leftarrow j$? Where $j = i \pm 1, i \pm 2, ..$

Proposed test for clustering correlated bins (?)

↓

Compute common null space: $\boldsymbol{U}^{S_i}$

EVD of $\boldsymbol{R}^{S_i} = \sum_{j \in S_i} \frac{1}{\hat{p}_r^j} (\widehat{\boldsymbol{R}}^j - \boldsymbol{R}_w^j)$

$\hat{p}_r^j$: Est. received power in bin j

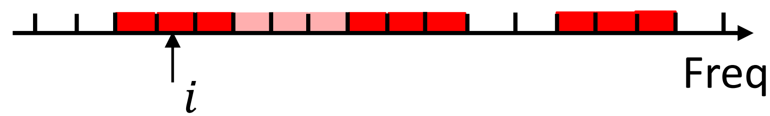
↓

Proposed Algorithm

$\boldsymbol{r}^f(n), f \in F_a$: set of bins with at least one PU

Bins in set F_a

Clustered bins



↓

Estimate covariance matrices $\widehat{\boldsymbol{R}}^f, f \in F_a$ using T samples of $\boldsymbol{r}^f(n), n = 1, \ldots, T$

↓

$i \leftarrow$ Center bin of new cluster. Compute null space $\boldsymbol{U}^i$ at bin i

EVD of $\widehat{\boldsymbol{R}}^i - \boldsymbol{R}_w^i$

$\boldsymbol{R}_w^i$: noise covariance

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Form cluster S_i around bin i. $S_i \leftarrow j$? Where $j = i \pm 1, i \pm 2, \ldots$

Proposed test for clustering correlated bins (?)

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Compute common null space: $\boldsymbol{U}^{S_i}$

EVD of $\boldsymbol{R}^{S_i} = \sum_{j \in S_i} \frac{1}{\hat{p}_r^j} (\widehat{\boldsymbol{R}}^j - \boldsymbol{R}_w^j)$

$\hat{p}_r^j$: Est. received power in bin j

$F_a = F_a \setminus S_i$

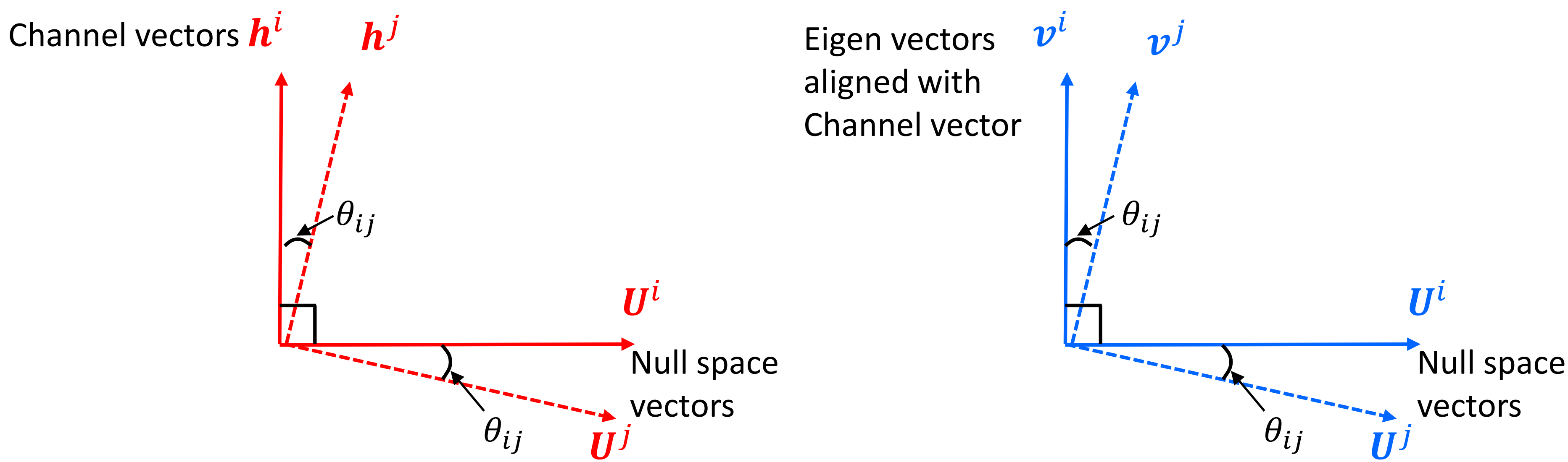
Repeat until $F_a = \phi$

↓

S:Set of clusters S_i,
null spaces $\boldsymbol{U}^{S_i}$

Number of EVD computations = 2 $|S|$

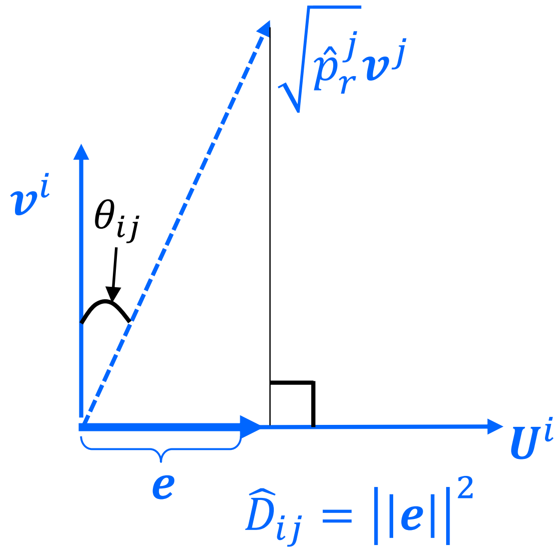
Null Spaces in Correlated Bins



- $\boldsymbol{v}^i$: Eigen vector of $\widehat{\boldsymbol{R}}^i - \boldsymbol{R}_w^i$ aligned with channel vector $\boldsymbol{h}^i$
- Higher $C_{ij} = \cos^2(\theta_{ij}) \Rightarrow$ more aligned null spaces $\boldsymbol{U}^i, \boldsymbol{U}^j$

  $\Rightarrow$ Bin j can be clustered with bin i.

Criterion for Clustering bin j with i



$\hat{p}_r^j = \mathrm{Tr}\left(\widehat{\boldsymbol{R}}^j - \boldsymbol{R}_w^j\right)$: Est. received power in bin j

$\widehat{D}_{ij}$: Component of $\hat{p}_r^j$ null space $\boldsymbol{U}^i$

$\uparrow$ Correlation $C_{ij} \Rightarrow \downarrow \theta_{ij} \Rightarrow \downarrow \widehat{D}_{ij}$

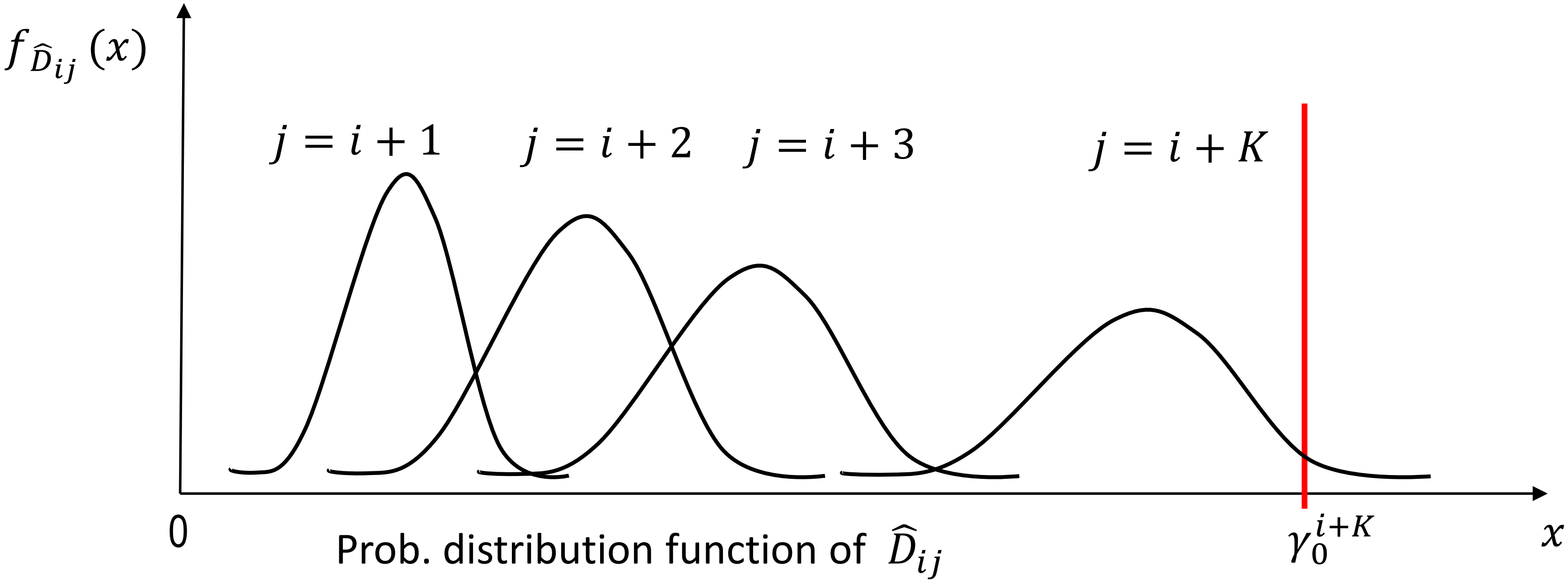
- $\widehat{D}_{ij} = \mathrm{Tr}\left(\left(\boldsymbol{U}^i\right)^H\left(\widehat{\boldsymbol{R}}^j - \boldsymbol{R}_{\boldsymbol{w}}^j\right)\boldsymbol{U}^i\right) \sim N\left((1 - C_{ij})\mu_j, (1 - C_{ij})^2\sigma_j^2\right)$.
  - $\mu_j = \mathrm{Tr}\left(\boldsymbol{R}^j - \boldsymbol{R}_w^j\right), \sigma_j^2 = \frac{\mu_j^2 + \sigma_w^2}{T}$, $\hat{p}_r^j \sim N\left(\mu_j, \sigma_j^2\right)$.
- $\widehat{D}_{ij}$ is Gaussian due to non-asymptotic estimation.
- Cluster j with i ($S_i \leftarrow j$) if $\widehat{D}_{ij} \leq \gamma_0^j$.
- Computations for $\widehat{D}_{ij}$ ($\approx 2M^3$ flops) $\ll$ computations for EVD ($\approx 23M^3$ flops) [5].

[5] Arakawa, "Computational workload for commonly used signal processing kernels", Project Report SPR-9, MIT Lincoln Lab., 2006.

Selection of Threshold γ_0^j

- To cluster bins with correlation $C_{ij} \geq 1 - \delta_0$ with probability P_0

$$\hat{D}_{ij} \leq \gamma_0^j = \delta_0 \sigma_j \, Q^{-1}(1 - P_0) + \delta_0 \mu_j$$



Larger $\boldsymbol{\delta_0}$ ⇒ larger threshold ⇒ more bins will be clustered with bin $\boldsymbol{i}$

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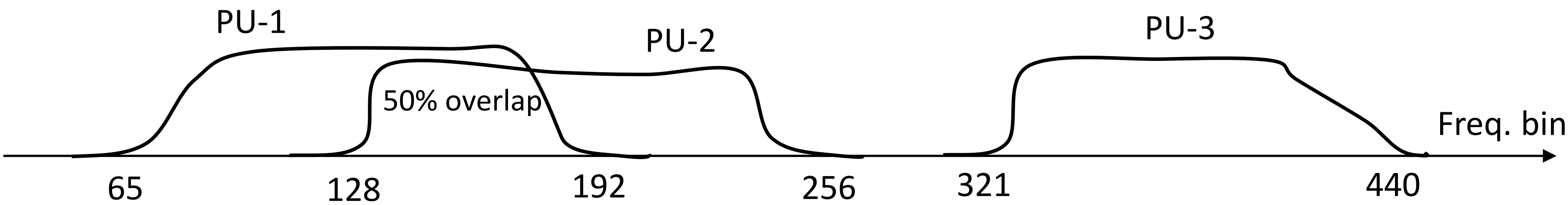
- **Conclusion**

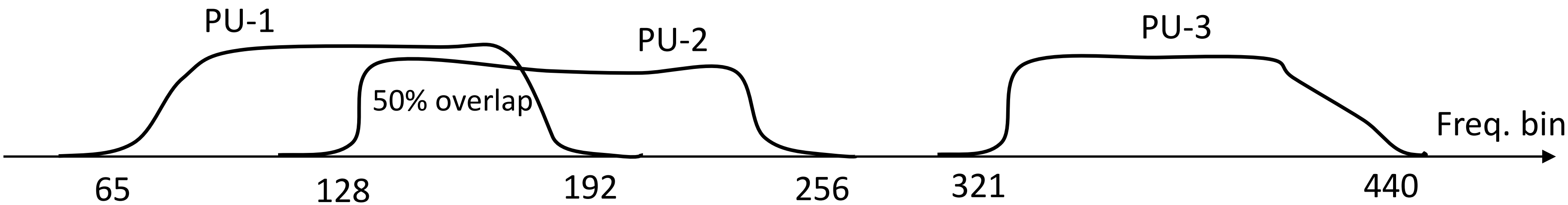
Simulation Setting

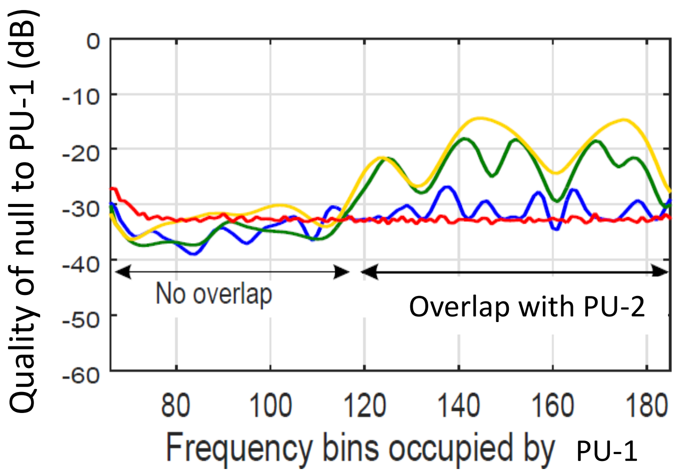
- BS parameters: $M = 8$ antennas, $F_s = 20$MHz, $F = 512$ bins.
- 3 PUs transmitting OFDM signals with bandwidths 5MHz. Average RX SNR = 10dB.

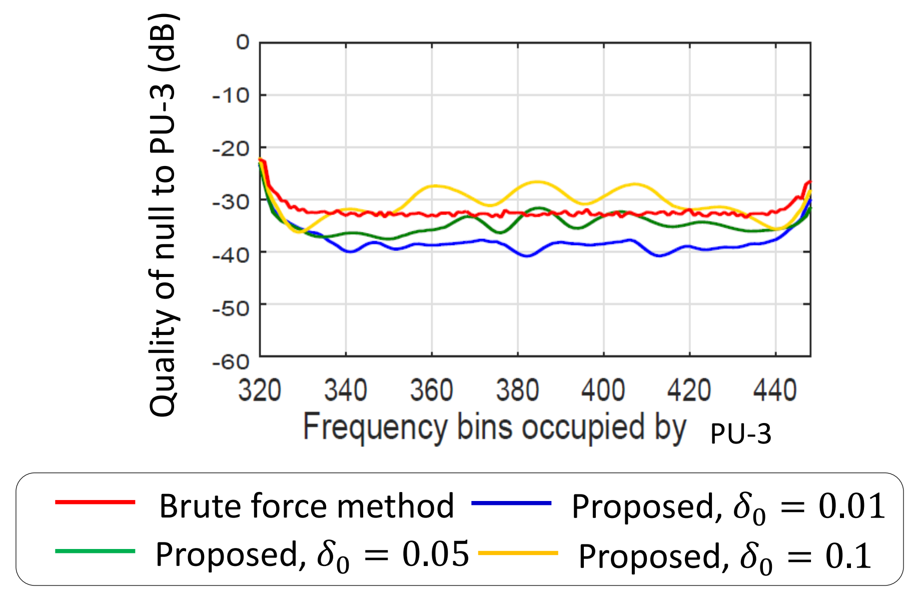


- Number of occupied bins = 312.
- # samples to estimate non-asymptotic $\widehat{\boldsymbol{R}}^i$: $T = 100$.
- Noise is white Gaussian: $\boldsymbol{R}_w^i = \boldsymbol{I}$.
- Algorithm parameters: $P_0 = 0.95,\ \delta_0 \in \{0.01, 0.05, 0.1\}$.
- Performance metrics:
  - Quality of null to PU-l : $\left|\left|\boldsymbol{U}^i \boldsymbol{h}_l^i\right|\right|^2 / \left|\left|\boldsymbol{h}_l^i\right|\right|^2$
  - Complexity: number of EVD computations.

Impact of δ_0 on Quality of Null



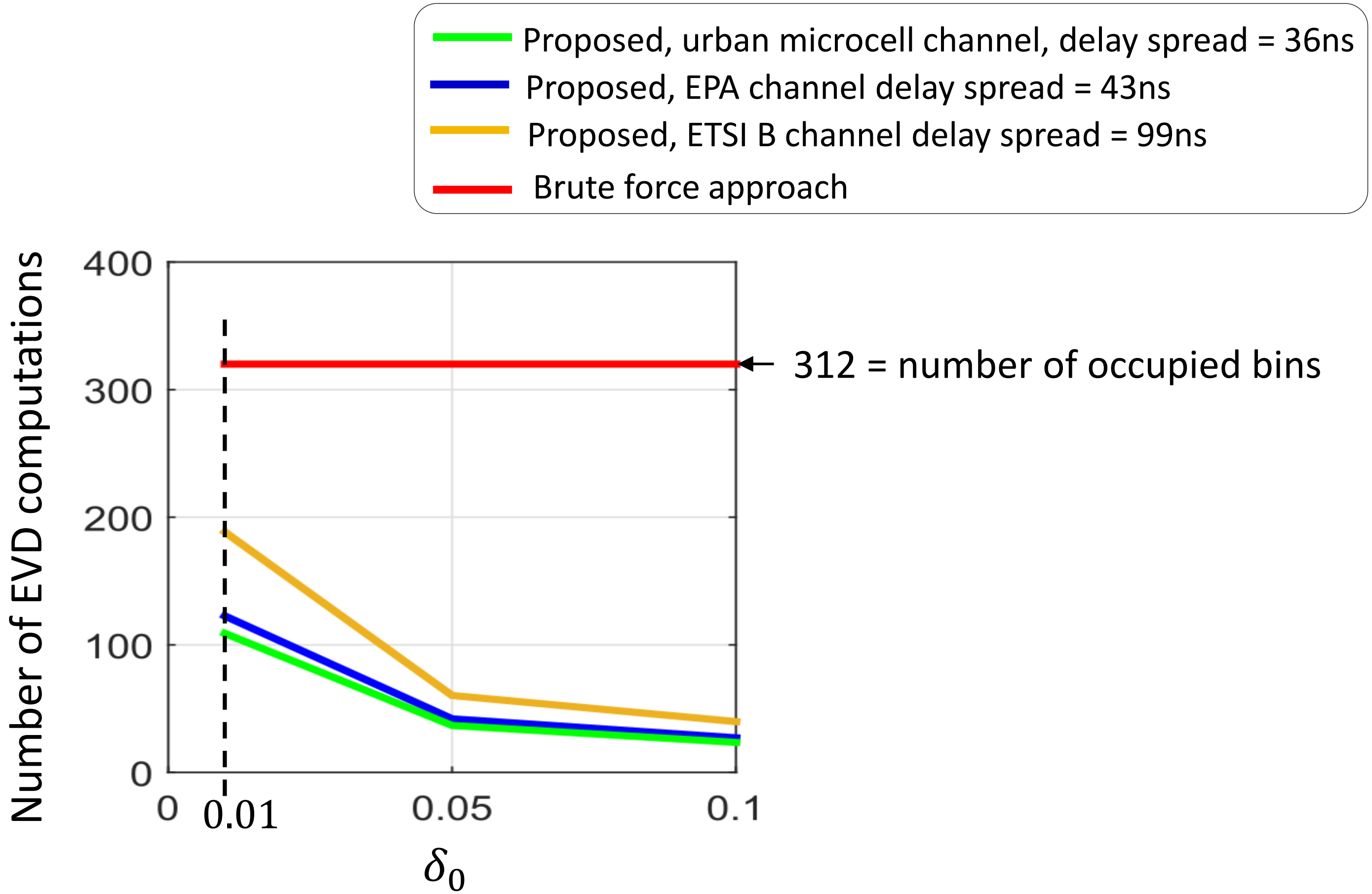




Channel: Urban microcell (delay spread 36ns)

- Use larger δ_0, e.g., $\delta_0 = 0.1$, in non-overlapped band to get same null quality as brute force method.
- In overlapped band, smaller clusters (hence $\delta_0 = 0.01$) are required to achieve comparable performance as brute force method.

Impact of Channel Model on Complexity



- Smaller delay spread ⇒ more bins per cluster⇒ reduced # EVD computations
- $\delta_0 = 0.1$ for non-overlapped bins reduces complexity up to 1/10.
- $\delta_0 = 0.01$ for overlapped bins will reduce complexity up to 1/3.

Conclusion

- **Proposed frequency clustering for wideband null steering**
  - Does not require prior knowledge of channels or training.
  - Reduces complexity of wideband null space estimation
    - Number of EVDs reduced by 1/3 to 1/10 as compared to brute force.
  - Number of computations depend on embedded correlation in the channels.

Thank you very much!

Questions?

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