Compressed Beam-Selection In Millimeter Wave Systems With Out-of-band Partial Support Information

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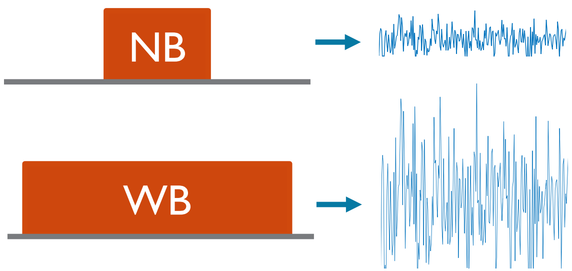
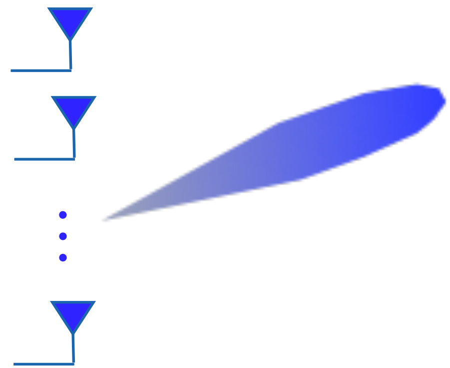
Channel estimation followed by beam-selection

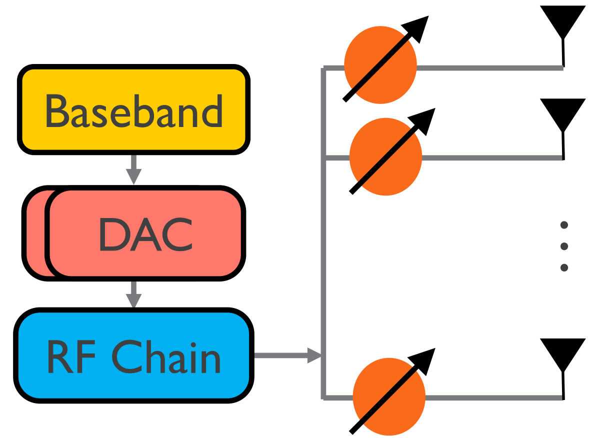
Low SNR w/o BF



Large Tx/Rx Arrays

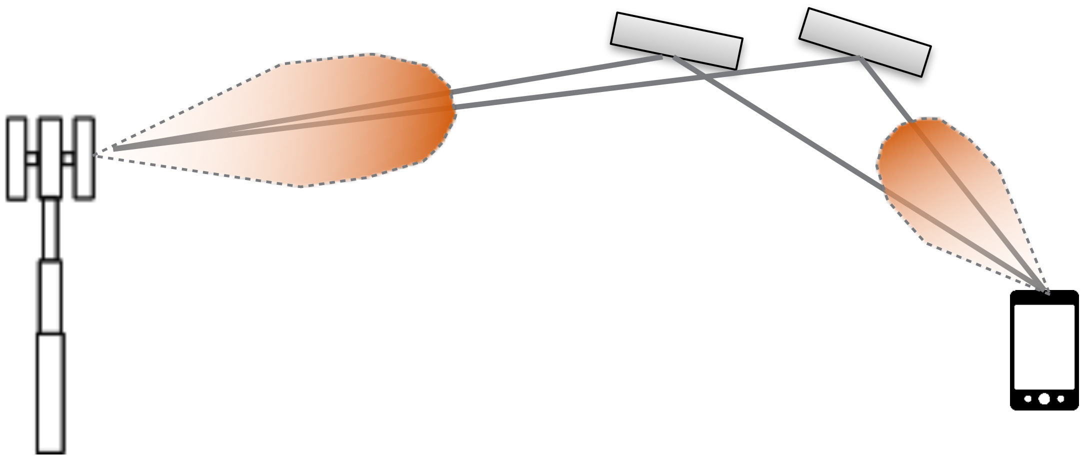


Hardware Constraints



MmWave channel estimation a challenging problem

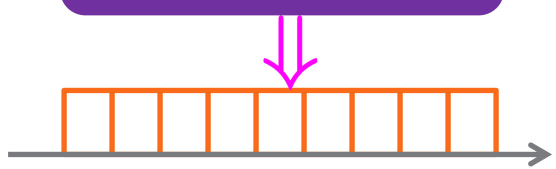
Good news: MmWave channels are sparse



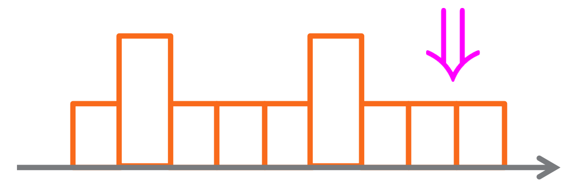
Poor scattering
⇓
Spatially sparse
⇓
Compressed sensing
[Alk’14][Alk’15]

No other *Structure* is exploited

No prior Information (assume uniform)



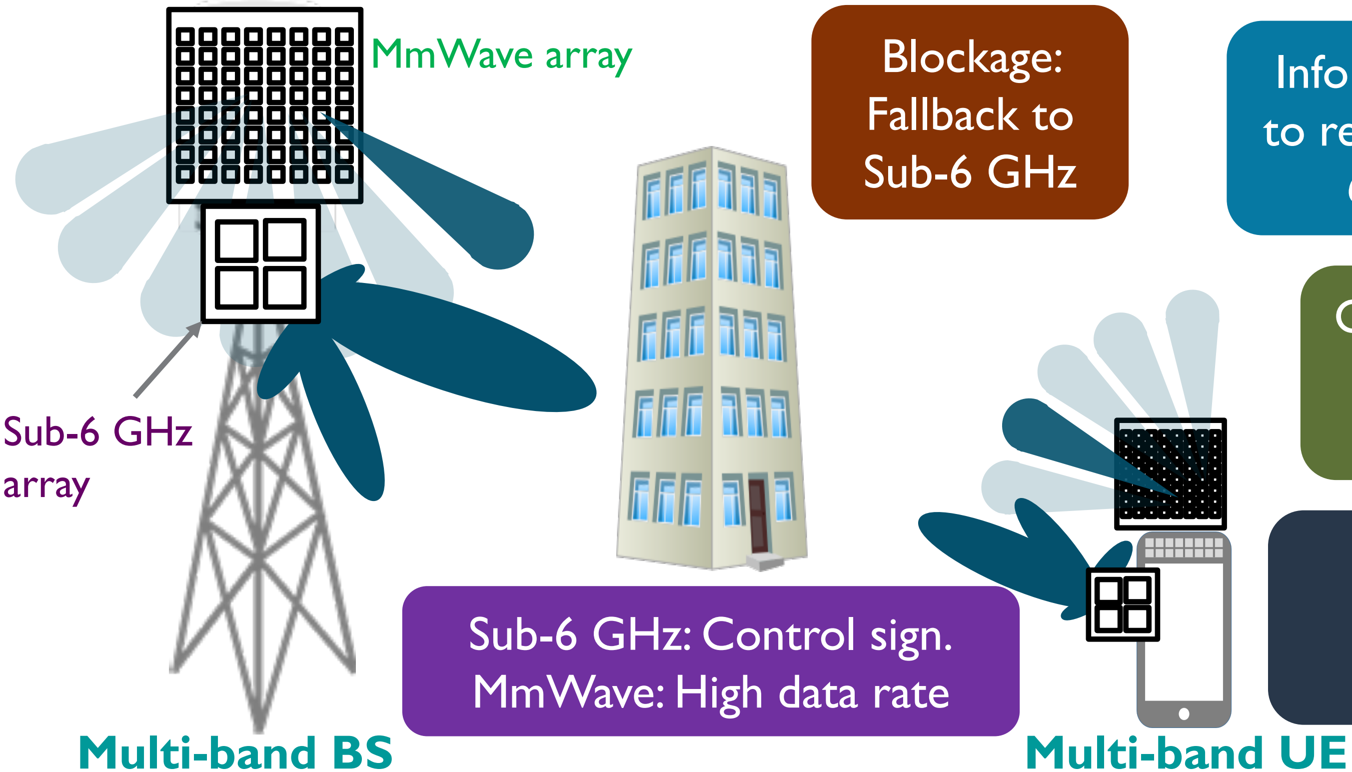
A priori support Information



[Alk’14] A. Alkhateeb, O. El Ayach, G. Leus, and R. W. Heath Jr., “Channel estimation and hybrid precoding for millimeter wave cellular systems,” IEEE J. Sel. Topics Signal Process., vol. 8, no. 5, pp. 831–846, 2014.

[Alk’15] A. Alkhateeb, G. Leus, and R. W. Heath Jr., “Compressed sensing based multi-user millimeter wave systems: How many measurements are needed?” in Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP), April 2015, pp. 2909–2913.

Sub-6 GHz/mmWave multi-band communication



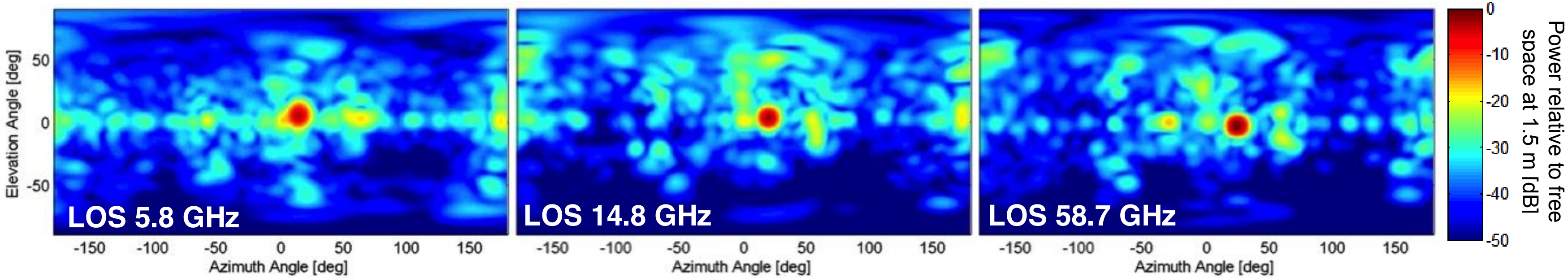
Information from legacy WiFi to reduce training overhead in 60 GHz WiFi [Nit'15]

Correlation translation from Sub-6 GHz to mmWave [Ali'16]

Optimal Sub-6 GHz/ mmWave scheduling [Hash'17]

[Nit'15] T. Nitsche, A. B. Flores, E. W. Knightly, and J. Widmer, "Steering with eyes closed: mm-wave beam steering without in-band measurement," in Proc. IEEE Int. Conf. Comput. Commun. (INFOCOM), 2015, pp. 2416– 2424.
[Ali'16] A. Ali, N. G. Prelcic, and R. W. Heath Jr., "Estimating Millimeter Wave Channels using Out-of-Band Measurements," in Proc. Inf. Theory Appl. (ITA) Wksp, 2016, pp. 1–5.
[Hash'17] M. Hashemi, , C. E. Koksal and N. B. Shroff, "Hybrid RF-mmWave Communications to Achieve Low Latency and High Energy Efficiency in 5G Cellular Systems", arXiv preprint arXiv:1701.06241.

Spatial congruence in sub-6 GHz and mmWave



Directional power distribution profile at three frequencies [Perter'16]

Similar power delay profile for 10 GHz and 30 GHz [Dupleich'16]

Minor differences in CDFs of Azimuth/Elevation AoA/AoD spread [Ky'16]

[Peter'16] M. Peter *et al.*, "Measurement campaigns and initial channel models for preferred suitable frequency ranges," Millimeter-Wave Based Mobile Radio Access Network for Fifth Generation Integrated Communications, Tech. Rep., Mar. 2016.
[Dupleich'16] D. Dupleich *et al.*, "Simultaneous multi-band channel sounding at mm-Wave frequencies," in *Proc. Eur. Conf. Antennas Propag. (EuCAP)*, Apr. 2016, pp. 1–5.
[Ky'17] P.Ky *et al.*,"Frequency dependency of channel parameters in urban LOS scenario for mmwave communications," in *Proc. Eur. Conf. Antennas Propag. (EuCAP)*, Apr. 2016, pp. 1–5.

Contributions

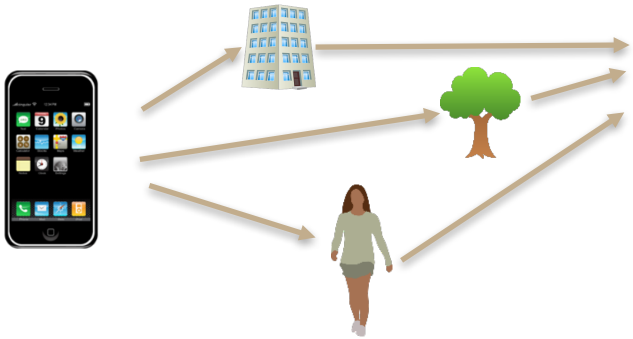
Propose out-of-band aided compressed beam-selection

- Beam-selection via weighted ℓ_1-minimization
- Extract weighting information from sub-6 GHz

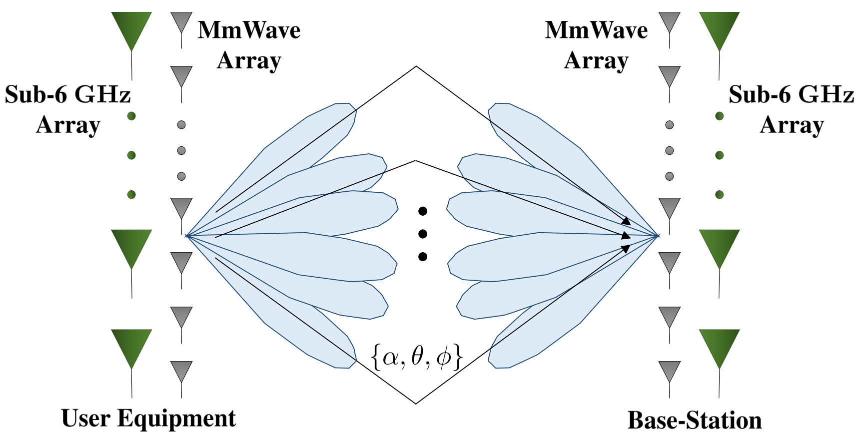
Comparison with in-band beam-selection

- Provides insights: When is weighted ℓ_1-minimization beneficial?

System and channel model



User Equipment | Channel | Base Station



Key Aasumptions

- Narrowband Sub-6 GHz/mmWave
- Coherence time
- Aligned ULAs for sub-6 GHz/mmWave
- Fully digital sub-6 GHz
- Analog mmWave
- Sub-6 GHz and mmWave operate simultaneously

Sub-6 GHz variables are underlined

Geometric channel model

$$\mathbf{H} = \sqrt{\frac{M_{\mathrm{UE}} M_{\mathrm{BS}}}{P}} \sum_{p=1}^{P} \alpha_p \mathbf{a}_{\mathrm{BS}}(\nu_p) \mathbf{a}^*_{\mathrm{UE}}(\omega_p)$$

UE antennas; BS antennas; Number of paths; Channel; Path Gain; Array response vectors; AoA/AoD

$$\omega \triangleq \sin(\phi)$$

$$\nu \triangleq \sin(\theta)$$

MmWave beam-selection

Exhaustive search

Realize DFT codebook

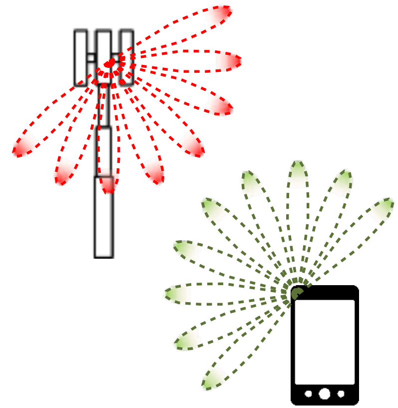
$\mathbf{A}_{\mathrm{UE}}$

with

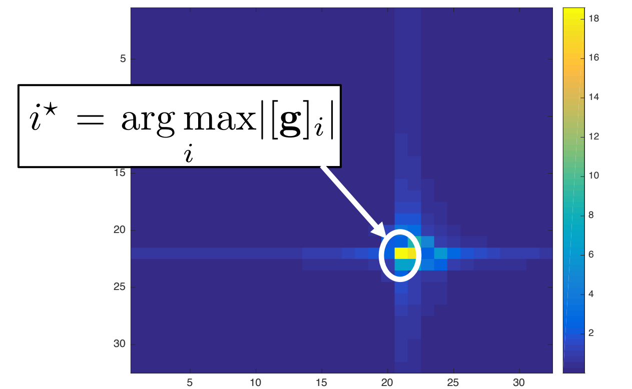
$D_{\mathrm{UE}} = \log_2(M_{\mathrm{UE}})$

bit phase-shifters

Also for BS get $\mathbf{A}_{\mathrm{BS}}$



$$\mathbf{G} = \mathbf{A}_{\mathrm{BS}}^{*}\mathbf{H}\mathbf{A}_{\mathrm{UE}}$$



$$\mathbf{g} = \mathrm{vec}(\mathbf{G}) = (\mathbf{A}_{\mathrm{UE}}^{\mathsf{T}} \otimes \mathbf{A}_{\mathrm{BS}}^{*})\mathrm{vec}(\mathbf{H})$$

Compressed beam-selection

$$y_{n,m} = \mathbf{q}_n^{*}\mathbf{H}\mathbf{f}_m s_m + \mathbf{q}_n^{*}\mathbf{v}_{n,m}$$

- $y_{n,m}$: N_{BS} x N_{UE} outputs
- $\mathbf{q}_n^{*}$: N_{BS} combiners
- $\mathbf{f}_m$: N_{UE} precoders
- s_m: Transmission symbol

Collectively $\mathbf{Y} = \sqrt{E_s}\mathbf{Q}^{*}\mathbf{H}\mathbf{F} + \mathbf{V}$

- $\mathbf{Q}^{*}$: Collective combiner
- $\mathbf{F}$: Collective precoder

Vectorized measurement vector

$$\mathbf{y} = \sqrt{E_s}(\mathbf{F}^{\mathsf{T}} \otimes \mathbf{Q}^{*})\mathrm{vec}(\mathbf{H}) + \mathrm{vec}(\mathbf{V})$$

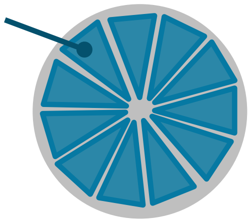
$$= \sqrt{E_s}(\mathbf{F}^{\mathsf{T}} \otimes \mathbf{Q}^{*})(\mathbf{A}_{\mathrm{UE}}^{c} \otimes \mathbf{A}_{\mathrm{BS}})\mathbf{g} + \mathrm{vec}(\mathbf{V})$$

- $(\mathbf{F}^{\mathsf{T}} \otimes \mathbf{Q}^{*})$: Combined precoding/combing matrix realized using analog beamforming
- $(\mathbf{A}_{\mathrm{UE}}^{c} \otimes \mathbf{A}_{\mathrm{BS}})$: Dictionary: Columns are uniformly spaced samples of BS/UE arrays
- $\mathbf{g}$: Sparse unknown

Out-of-band aided compressed beam-selections

Measurement matrix → $\mathbf{\Phi} = \sqrt{E_s}(\mathbf{F}^{\mathsf{T}} \otimes \mathbf{Q}^*)$ Dictionary matrix → $\mathbf{\Psi} = (\mathbf{A}_{\mathrm{UE}}^{c} \otimes \mathbf{A}_{\mathrm{BS}})$

The best beam can be any beam with equal probability



ℓ_1-minimization

$$\begin{aligned} &\text{minimize} && \|\mathbf{g}\|_1 \\ &\text{subject to} && \|\mathbf{y} - \mathbf{\Phi}\mathbf{\Psi}\mathbf{g}\|_2 \leq \epsilon \end{aligned}$$

ϵ → Tolerance

With prior info solve weighted ℓ_1-minimization instead

Weighted ℓ_1-minimization

$$\begin{aligned} &\text{minimize} && \|\mathbf{g}\|_{\mathbf{w},1} \\ &\text{subject to} && \|\mathbf{y} - \mathbf{\Phi}\mathbf{\Psi}\mathbf{g}\|_2 \leq \epsilon \end{aligned}$$

[Fr'12][Sc'13]

$$\|\mathbf{g}\|_{\mathbf{w},1} = \sum_{i=1}^{M_{\mathrm{UE}}M_{\mathrm{BS}}} [\mathbf{w}]_i |[\mathbf{g}]_i|$$

Entries of the weighting vector

Out-of-band information about likely beams

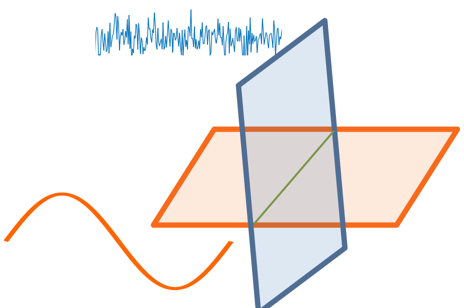
[Fr'12] M. P. Friedlander *et al.*, "Recovering compressively sampled signals using partial support information," *IEEE Trans. Inf. Theory*, vol. 58, no. 2, pp. 1122–1134, Feb. 2012.
[Sc'13] J. Scarlett, J. S. Evans, and S. Dey,"Compressed sensing with prior information: Information-theoretic limits and practical decoders," *IEEE Trans. Signal Process.*, vol. 61, no. 2, pp. 427–439, Jan 2013.

Angle estimation at Sub-6 GHz

Geometric channel for sub-6 GHz

Distinguish sub-6 GHz with underline

Empirical estimate $\widehat{\underline{\mathbf{R}}_{\tilde{\mathbf{r}}}}$



Noise subspace

⊥

Signal subspace

$$\underline{\mathbf{R}}_{\tilde{\mathbf{r}}} = \underline{\mathbf{U}}_{\alpha} \underline{\boldsymbol{\Lambda}}_{\alpha} \underline{\mathbf{U}}_{\alpha}^{*} + \underline{\mathbf{U}}_{\mathbf{v}} \underline{\boldsymbol{\Lambda}}_{\mathbf{v}} \underline{\mathbf{U}}_{\mathbf{v}}^{*}$$

P-eigenvectors of the signal subspace

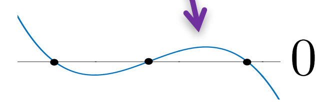
$M_{UE}M_{BS}$ - P Noise subspace eigenvectors

Definition $\underline{\mathbf{c}}(\phi, \theta) = \underline{\mathbf{a}}_{\mathrm{UE}}^{c}(\phi) \otimes \underline{\mathbf{a}}_{\mathrm{BS}}(\theta)$

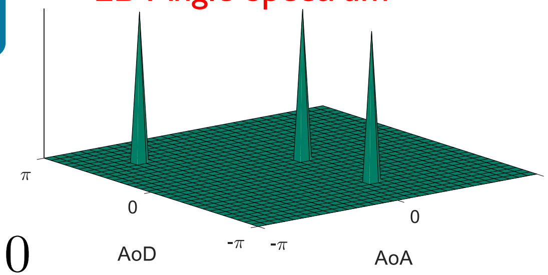
In source direction $\underline{\mathbf{c}}(\phi, \theta)^{*} \underline{\mathbf{U}}_{\mathbf{v}} \underline{\mathbf{U}}_{\mathbf{v}}^{*} \underline{\mathbf{c}}(\phi, \theta) = 0$

Root-MUSIC

$\underline{\mathbf{c}}(\phi, \theta)^{*} \underline{\mathbf{U}}_{\mathbf{v}} \underline{\mathbf{U}}_{\mathbf{v}}^{*} \underline{\mathbf{c}}(\phi, \theta)$



2D Angle Spectrum



Make a polynomial in ϕ, θ and Find roots

Double Root-MUSIC [Ben'10]

Can detect (RX Ant.)x(TX Ant. - 1) angles

Automatic AoA/AoD Pairing
No mismatch

[Ben'10] M. L. Bencheikh, Y. Wang, and H. He, "Polynomial root finding technique for joint DOA DOD estimation in bistatic MIMO radar," Signal Process., vol. 90, no. 9, pp. 2723–2730, 2010.

Weight calculation

Recall that we want to solve

$$\begin{aligned} \text{minimize} \quad & \|\mathbf{g}\|_{\mathbf{w},1} \\ \text{subject to} \quad & \|\mathbf{y} - \mathbf{\Phi\Psi g}\|_2 \leq \epsilon \end{aligned}$$

Sub-6 GHz/mmWave mismatch

$$\rho_{\text{mis}} = 1 - \frac{1}{P}\mathbb{E}\left[|\mathcal{A} \cap \underline{\mathcal{A}}|\right]$$

$$\omega \triangleq \sin(\phi)$$

$$\nu \triangleq \sin(\theta)$$

Sub-6 GHz angles

$$\underline{\mathcal{A}} = \{(\underline{\omega}_1, \underline{\nu}_1), \cdots, (\underline{\omega}_P, \underline{\nu}_P)\}$$

MmWave angles

$$\mathcal{A} = \{(\omega_1, \nu_1), \cdots, (\omega_P, \nu_P)\}$$

Accuracy of angle estimation algorithm works

$$\rho_{\text{sdrm}} = \mathbb{E}\left[\mathbb{1}\{|\underline{\omega}_p - \hat{\underline{\omega}}_p| < M_{\text{UE}}^{-1}, |\underline{\nu}_p - \hat{\underline{\nu}}_p| < M_{\text{BS}}^{-1}\}\right]$$

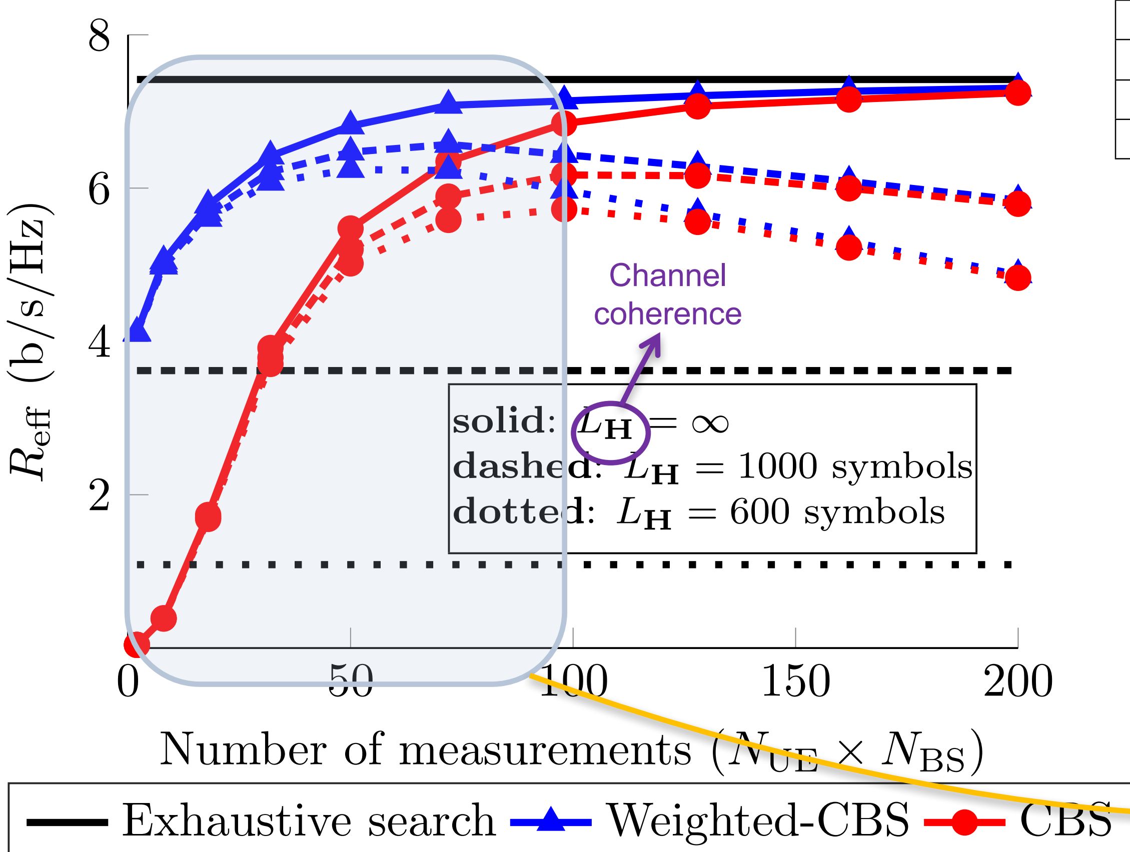
Weight calculation

$$[\mathbf{w}]_{\mathcal{P}} = 1 - \rho_{\text{sdrm}}(1 - \rho_{\text{mis}})$$

Corresponding to the dominant angles

$$[\mathbf{w}]_{\{1,2,\cdots,M_{\text{UE}} \times M_{\text{BS}}\} \setminus \mathcal{P}} = \rho_{\text{sdrm}}(1 - \rho_{\text{mis}})$$

Simulation results I



Parameter	Value	Parameter	Value
M_{UE}	16	M_{BS}	32
$\underline{M}_{\text{UE}}$	2	$\underline{M}_{\text{BS}}$	4
f	28 GHz	$\underline{f}$	3.5 GHz
Δ	1/2	$\underline{\Delta}$	1/2
D_{UE}	4	D_{BS}	5

Observations

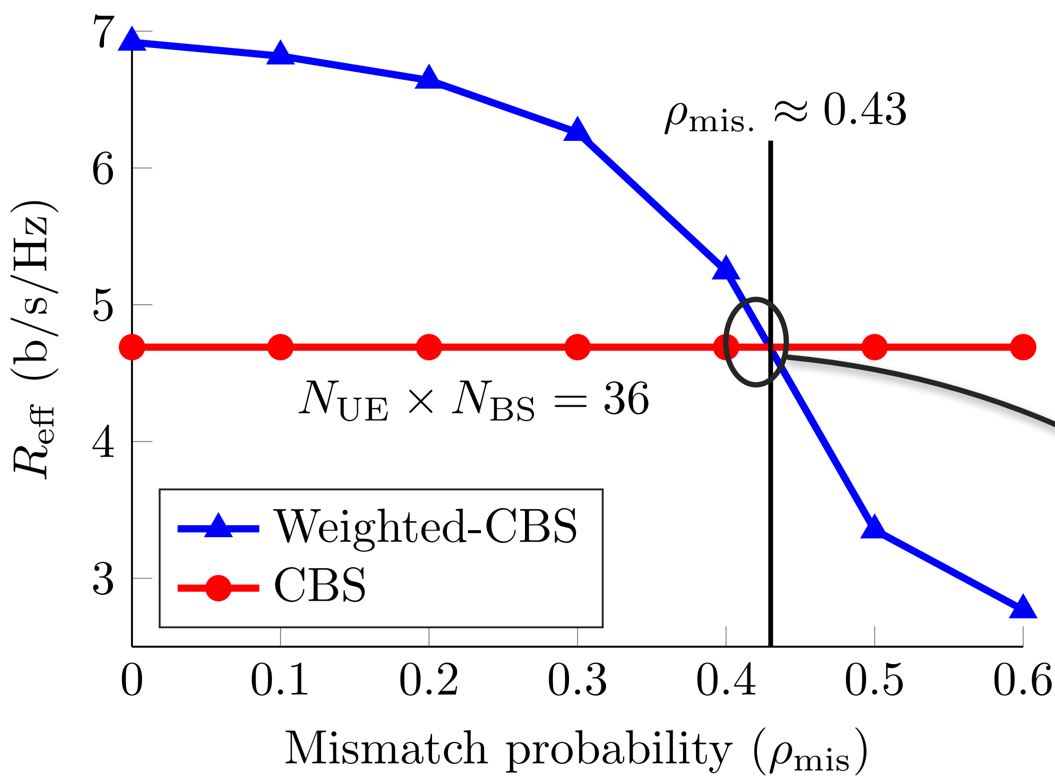
Out-of-band information useful with a few measurements

With small coherence time, the benefit is more pronounced with small coherence time

Region of interest
from
mmWave beam-selection
point of view

Simulation results II

Parameter	Value	Parameter	Value
M_{UE}	16	M_{BS}	32
$\underline{M}_{\text{UE}}$	2	$\underline{M}_{\text{BS}}$	4
f	28 GHz	$\underline{f}$	3.5 GHz
Δ	1/2	$\underline{\Delta}$	1/2
D_{UE}	4	D_{BS}	5



Observations

Out-of-band information useful when the sub-6 GHz and mmWave channel's dominant AoA/AoD are similar

If the dominant AoA/AoD are substantially different, in-band only training is more beneficial

Agrees with previous theoretical findings [Fr'12]

[Fr'12] M. P. Friedlander *et al.*, "Recovering compressively sampled signals using partial support information," *IEEE Trans. Inf. Theory*, vol. 58, no. 2, pp. 1122–1134, Feb. 2012.

Conclusions and Future Work

Weighted CS based Recovery is promising to reduce overhead in comparison with traditional CS, much lower than exhaustive search

Beneficial when the dominant AoA/AoD at sub-6 GHz and mmWave are similar

Extensions to other array geometries, hybrid analog/digitial or fully digital architectures at mmWave

Questions?

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