Low-Overhead Receiver-side Channel Tracking for mmWave MIMO

Karthik Upadhya[†], Sergiy A. Vorobyov[†], and Robert W. Heath, Jr.[*]

Department of Signal Processing and Acoustics, Aalto University[†]
Wireless Networking and Commmunications Group, University of Texas at Austin[*]

Aalto University
School of Electrical Engineering

Introduction

- mmWave transceivers are expected to employ *large antenna arrays*.
- mmWave channels are *sparse* in the angular domain.
- The communication link is susceptible to changes in the AoA or AoD.
- In hybrid beamforming architectures, the transceiver can *look* only in a few directions.
- In use cases such as hand-held transceivers, drones etc., the AoAs change, but the AoDs remain constant.

Main Contribution

- Algorithm for blind subspace estimation at the receiver.
- AoAs are obtained from the estimated subspace.
- Useful for low-latency communication since a very low overhead is required.

System Model and Initial Channel Estimation

- Received observations in symbol k of downlink

$$\boldsymbol{y}[k] = \boldsymbol{W}^H\boldsymbol{H}\boldsymbol{F}\boldsymbol{s}[k] + \boldsymbol{W}^H\boldsymbol{q}[k]$$

$\boldsymbol{W} \in \mathbb{C}^{N_{\mathrm{UE}}\times N_s}$: Receive combiner, $\boldsymbol{F} \in \mathbb{C}^{N_{\mathrm{AP}}\times N_s}$: Transmit precoder
$\boldsymbol{H} \in \mathbb{C}^{N_{\mathrm{UE}}\times N_{\mathrm{AP}}}$: Channel matrix.

- Channel model (assuming ULA)

$$\boldsymbol{H} = \sum_{p=0}^{P-1} \alpha_p \boldsymbol{a}_{\mathrm{UE}}(\phi_p)\,\boldsymbol{a}_{\mathrm{AP}}^H(\psi_p) = \boldsymbol{A}_{\mathrm{UE}}\boldsymbol{D}\boldsymbol{A}_{\mathrm{AP}}^H \approx \bar{\boldsymbol{A}}_{\mathrm{UE}}\bar{\boldsymbol{D}}\bar{\boldsymbol{A}}_{\mathrm{AP}}^H$$

$\boldsymbol{a}_{\mathrm{UE}}(\cdot)$ and $\boldsymbol{a}_{\mathrm{AP}}(\cdot)$: steering vector at the UE and AP.
α_p, ϕ_p, and ψ_p : Path gain, AoA, and AoD of path p.
$\bar{\boldsymbol{A}}_{\mathrm{AP}}$, $\bar{\boldsymbol{A}}_{\mathrm{UE}}$: Matrix of steering vectors containing quantized angles.
$\bar{\boldsymbol{D}} \in \mathbb{C}^{G_{\mathrm{UE}}\times G_{\mathrm{AP}}}$: sparse matrix with non-zero locations corresponding to the AoA and AoD pairs.

- M_{AP} training symbols transmitted by AP. UE makes M_{UE} measurements for each training symbol.
- $J \triangleq M_{\mathrm{AP}}M_{\mathrm{UE}}$ received observations for training :

$$\boldsymbol{Y} = \boldsymbol{W}^H\boldsymbol{H}\boldsymbol{F} + \boldsymbol{Q} \approx \boldsymbol{W}^H\bar{\boldsymbol{A}}_{\mathrm{UE}}\bar{\boldsymbol{D}}\bar{\boldsymbol{A}}_{\mathrm{AP}}^H\boldsymbol{F} + \boldsymbol{Q}$$

- Sparse recovery of channel :

$$\widehat{\boldsymbol{d}} = \min_{\boldsymbol{d}} \|\boldsymbol{d}\|_0 \ \text{ subject to } \ \|\boldsymbol{y} - \boldsymbol{\Psi}\boldsymbol{d}\|_2 \le \epsilon$$

$\boldsymbol{y} \triangleq \mathrm{vec}(\boldsymbol{Y})$, $\boldsymbol{d} \triangleq \mathrm{vec}(\bar{\boldsymbol{D}})$, $\boldsymbol{\Psi} \triangleq \boldsymbol{F}^T\bar{\boldsymbol{A}}_{\mathrm{AP}}^* \otimes \boldsymbol{W}^H\bar{\boldsymbol{A}}_{\mathrm{UE}}$

Proposed Method

- Coherence block assumed to be divided into $M_{\mathrm{AP}} \times M_{\mathrm{UE}}$ sub blocks.
- During sub-block (m, n), AP uses precoder $\boldsymbol{F}_m$ and UE uses combiner $\boldsymbol{W}_n$.
- Hybrid architecture at the AP and UE
- $N_{\mathrm{UE}}^{\mathrm{RF-T}}$ ($N_{\mathrm{AP}}^{\mathrm{RF-T}}$) out of $N_{\mathrm{UE}}^{\mathrm{RF}}$ ($N_{\mathrm{AP}}^{\mathrm{RF}}$) reserved for channel estimation at the UE (AP).

$\Longrightarrow$ $\boldsymbol{W}_n \triangleq [\boldsymbol{W}^{\mathrm{d}}, \boldsymbol{W}_n^{\mathrm{t}}]$ and $\boldsymbol{F}_m \triangleq [\boldsymbol{F}^{\mathrm{d}}, \boldsymbol{F}_m^{\mathrm{t}}]$

- The covariance matrix of the observations within sub-block (m, n) :

$$\boldsymbol{R}_{m,n} \triangleq \mathbb{E}\left\{\boldsymbol{y}_{m,n}[k]\,\boldsymbol{y}_{m,n}^H[k]\right\} = \boldsymbol{W}_n^H\boldsymbol{H}\boldsymbol{F}_m\boldsymbol{F}_m^H\boldsymbol{H}^H\boldsymbol{W}_n + \sigma^2\boldsymbol{W}_n^H\boldsymbol{W}_n$$

- Summed over all m :

$$\boldsymbol{R}_n \triangleq \sum_{m=1}^{M_{\mathrm{AP}}} \boldsymbol{R}_{m,n} = \boldsymbol{W}_n^H\boldsymbol{X}\boldsymbol{W}_n + \sigma^2 M_{\mathrm{AP}}\boldsymbol{W}_n^H\boldsymbol{W}_n$$

$\boldsymbol{X} \triangleq \boldsymbol{H}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{H}^H$
$\boldsymbol{F} \triangleq [\boldsymbol{F}_1, \ldots, \boldsymbol{F}_{M_{\mathrm{AP}}}]$

Proposition

Let $\boldsymbol{H} = \boldsymbol{U}_s\boldsymbol{\Sigma}_s\boldsymbol{V}_s$. Then, $\mathrm{span}\{\boldsymbol{X}\} = \mathrm{span}\{\boldsymbol{U}_s\}$ if and only if $\boldsymbol{F}$ is chosen such that $\boldsymbol{V}_s^H\boldsymbol{F}$ has full row-rank.

$\Longrightarrow$ Basis vectors of $\mathrm{span}\{\boldsymbol{H}\}$ can be obtained without knowing $\boldsymbol{F}$ as long as $\boldsymbol{F}$ is such that AP transmits in the directions of all the AoDs of the channel.

Blind Subspace Estimation

- $\boldsymbol{X}$ is low-rank, therefore can be estimated using matrix completion methods.
- Alternatively, $\boldsymbol{X}$ can be sparsified using a dictionary and recovered using sparse reconstruction.
- Vectorizing $\{\boldsymbol{R}_n\}_{n=1}^{M_{\mathrm{UE}}}$ and stacking

$$\boldsymbol{r} \triangleq \begin{bmatrix} \boldsymbol{r}_1 \\ \vdots \\ \boldsymbol{r}_{M_{\mathrm{UE}}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\Psi}_1 \\ \vdots \\ \boldsymbol{\Psi}_{M_{\mathrm{UE}}} \end{bmatrix} \mathrm{vec}\left(\bar{\boldsymbol{D}}\boldsymbol{G}\bar{\boldsymbol{D}}^H\right) + \begin{bmatrix} \boldsymbol{q}_1 \\ \vdots \\ \boldsymbol{q}_{M_{\mathrm{UE}}} \end{bmatrix}$$

$\boldsymbol{G} \triangleq \bar{\boldsymbol{A}}_{\mathrm{AP}}^H\boldsymbol{F}\boldsymbol{F}^H\bar{\boldsymbol{A}}_{\mathrm{AP}}$
$\boldsymbol{\Psi}_n \triangleq \left(\left(\bar{\boldsymbol{A}}_{\mathrm{UE}}^H\boldsymbol{W}_n\right)^T \otimes \boldsymbol{W}_n^H\bar{\boldsymbol{A}}_{\mathrm{UE}}\right)$

- $\mathrm{vec}\left(\bar{\boldsymbol{D}}\boldsymbol{G}\bar{\boldsymbol{D}}^H\right)$ is sparse.
- The columns of $\bar{\boldsymbol{A}}_{\mathrm{UE}}$ corresponding to non-zero rows of $\bar{\boldsymbol{D}}$ span the column space of $\boldsymbol{H}$.

Choice of $\boldsymbol{F}_m^{\mathrm{t}}$ and $\boldsymbol{W}_n^{\mathrm{t}}$

- $\boldsymbol{F}_m^{\mathrm{t}}$ has to be chosen such that $\boldsymbol{V}_s^H\boldsymbol{F}$ is full rank.
- To avoid interference to transmitted data,

$$\boldsymbol{F}_m^{\mathrm{t}} = \boldsymbol{\Pi}_{\boldsymbol{F}^{\mathrm{d}}}^{\perp}\bar{\boldsymbol{F}}_m^{\mathrm{t}} = \left[\boldsymbol{I} - \boldsymbol{F}^{\mathrm{d}}\left(\boldsymbol{F}^{\mathrm{d}H}\boldsymbol{F}^{\mathrm{d}}\right)^{-1}\boldsymbol{F}^{\mathrm{d}H}\right]\bar{\boldsymbol{F}}_m^{\mathrm{t}}$$

- We have chosen $\boldsymbol{W}_n^{\mathrm{t}}$ to have random values $\Longrightarrow$ diffused beams in random directions.

Updating $\boldsymbol{W}^{\mathrm{d}}$

- Given a basis $\boldsymbol{B}$ for $\mathrm{span}\{\boldsymbol{U}_s\}$, $\boldsymbol{W}^{\mathrm{d}}$ can be chosen to satisfy ZF condition, i.e., $(\boldsymbol{W}^{\mathrm{d}})^H\boldsymbol{H}\boldsymbol{F}^{\mathrm{d}} = \boldsymbol{I}$.
- Resulting $\boldsymbol{W}^{\mathrm{d}} = \boldsymbol{B}\boldsymbol{P}^{\dagger}$ where $\boldsymbol{P} \triangleq \boldsymbol{B}^H\boldsymbol{H}\boldsymbol{F}^{\mathrm{d}}$.
- $\boldsymbol{P}$ can be estimated using $N_{\mathrm{UE}}^{\mathrm{RF-T}}$ pilot symbols.

Simulation Results

- $N_{\mathrm{AP}} = 64$ antennas, $N_{\mathrm{UE}} = 32$ antennas, $N_{\mathrm{AP}}^{\mathrm{RF}} = N_{\mathrm{UE}}^{\mathrm{RF}} = 4$, $N_{\mathrm{UE}}^{\mathrm{RF-T}} = 1$.
- $M_{\mathrm{AP}} = 12$ symbols, $M_{\mathrm{UE}} = 3$ symbols for initial channel estimation.
- For subspace estimation $M_{\mathrm{AP}} = 1$ and $M_{\mathrm{UE}} = 20$.
- Each block has 256 symbols. So, channel is constant for 5120 symbols.
- Channel has an LOS path with $\phi = 90°$ and NLOS cluster with 100 paths with angular spread $10°$ and mean angle $\phi = 45°$.
- NLOS is at 10dB lower power than LOS path.
- Angular difference between each block of 5120 symbols is distributed as $\mathcal{CN}(0, \sigma_\phi^2)$.
- Path amplitudes varies across coherence blocks according to Gauss Markov model with factor 0.8.

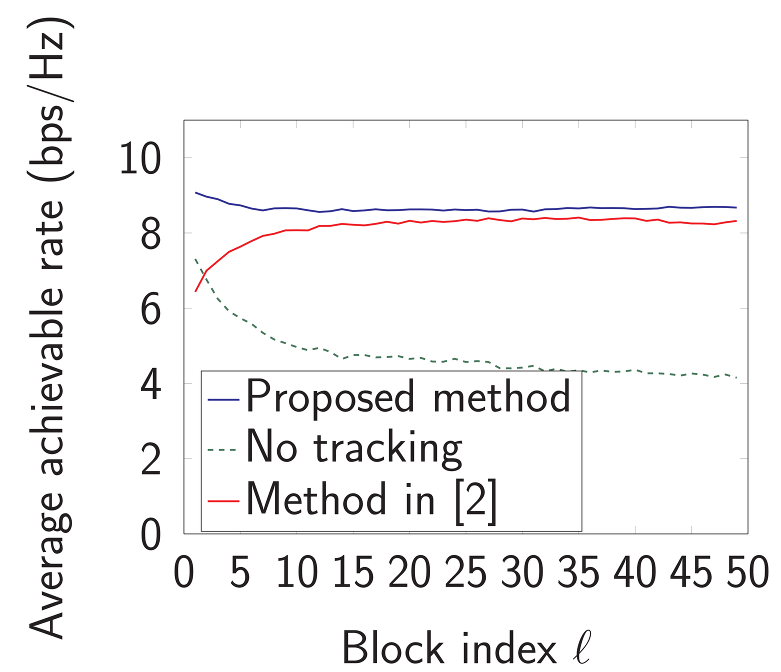

Figure: Plot of the average achievable rate vs block index at SNR = 0 dB, $\sigma_\phi = 2°$ and $\sigma_\psi = 0$

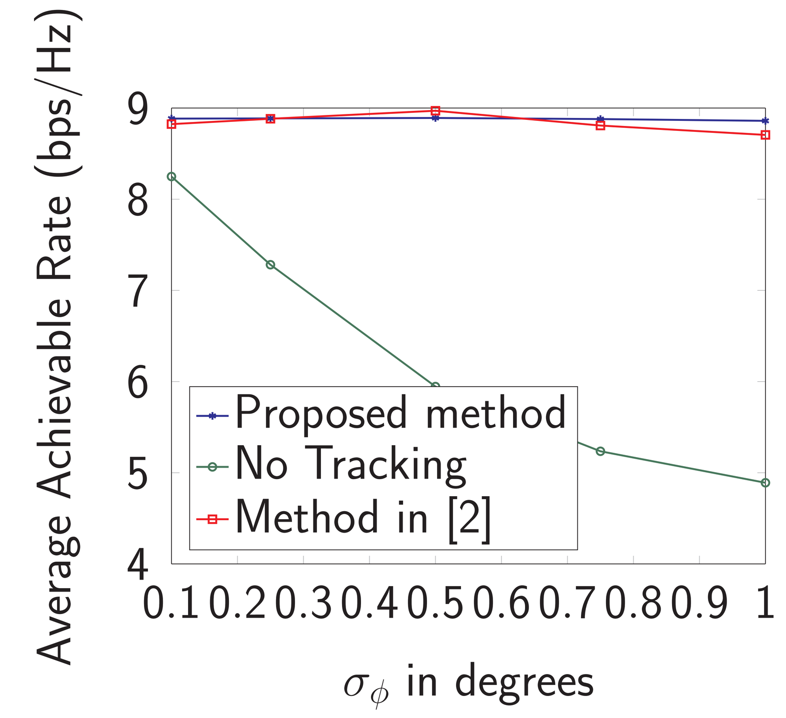

Figure: Plot of the average achievable rate vs σ_ϕ at SNR = 0 dB and $\sigma_\psi = 0$ at the $\ell = 50$th block.

Conclusion

- Proposed a blind channel tracking algorithm for mmWave MIMO.
- Possible research directions : Design $\boldsymbol{F}^{\mathrm{t}}$ and $\boldsymbol{W}^{\mathrm{t}}$ adaptively, extend to the multi-user case, and remove the requirement of dedicated RF chain for training are possible research directions.

References

[1] R. W. Heath, N. Gonzlez-Prelcic, S. Rangan, W. Roh and A. M. Sayeed, *An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems* IEEE J. Sel Topics Sig. Process., vol. 10, no. 3, pp. 436-453, April 2016.

[2] N. Garcia, H. Wymeersch, and D. T. M. Slock, *Optimal robust precoders for tracking the AoD and AoA of a mm-Wave path.* ArXiv, 2017, http://arxiv.org/abs/1703.10978.