# Deep Learning Based Hybrid Precoding in Dual-Band Communication Systems

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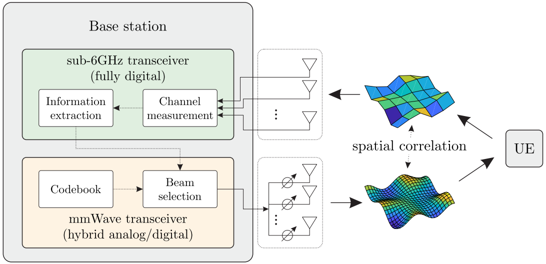
# Introduction

- Hybrid analog/digital beamforming is a promising technology for large-scale mmWave MIMO systems.
- The channel measured in the digital baseband is intertwined with the choice of analog precoders.
- The mmWave beamforming requires performing an exhaustive search over a finite set.
- There exists a correlation between the sub-6GHz and mmWave bands [1].

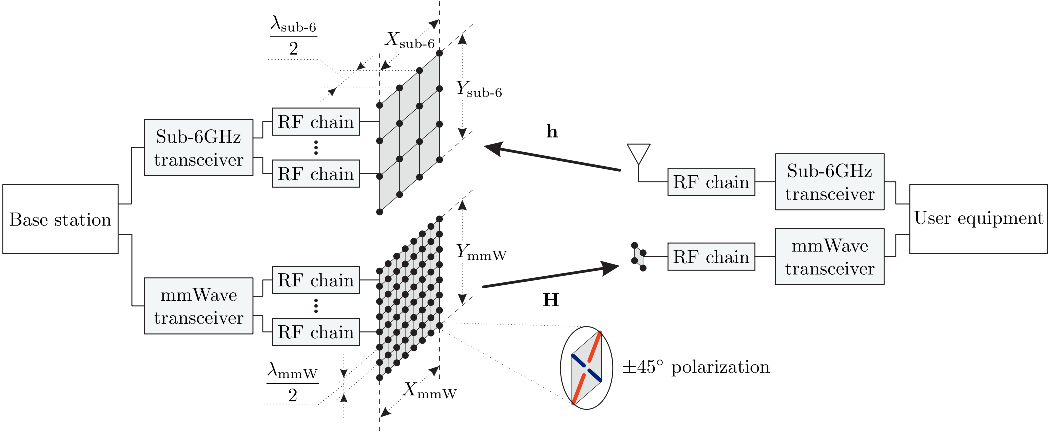
**Idea**

Utilize the correlation between sub-6GHz and mmWave bands to assist the beamforming in the mmWave band.



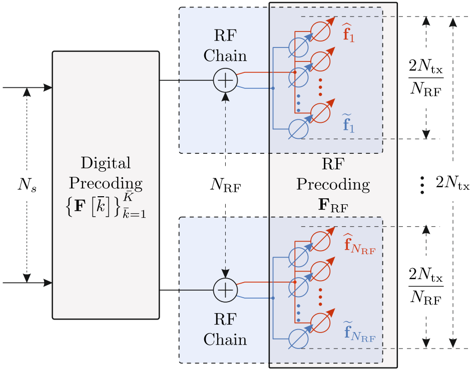

[1] Peter, M., et al. "Measurement Campaigns and Initial Channel Models for Preferred Suitable Frequency Ranges," Deliverable D2, vol. 1, pp. 160, 2016.

# Dual-Band Wireless MIMO-OFDM Communication System



# Hybrid Precoding with Subarray Structure

| mmWave transceiver with hybrid analog/digital architecture | |
|---|---|
| **System variable** | **Description** |
| $N_s$ | total number of data streams |
| $N_{\text{RF}}$ | total number of RF chains |
| $N_{\text{tx}} = X_{\text{mmW}} \times X_{\text{mmW}}$ | total number of antenna elements |
| $\bar{K}$ | total number of OFDM subcarriers |
| $\mathbf{F}\left[\bar{k}\right] \in \mathbb{C}^{N_{\text{RF}} \times N_s}$ | digital precoder at subcarrier $\bar{k}$ |
| $\mathbf{F}_{\text{RF}} \in \mathbb{C}^{2N_{\text{tx}} \times N_{\text{RF}}}$ | analog precoder |
| $(\forall r \in \{1, ..., N_{\text{RF}}\})\, \widehat{\mathbf{f}}_r \in \mathbb{C}^{N_{\text{tx}}/N_{\text{RF}}}$ | beamforming vector at the $r^{\text{th}}$ RF chain with $+45^\circ$ polarization |
| $(\forall r \in \{1, ..., N_{\text{RF}}\})\, \widetilde{\mathbf{f}}_r \in \mathbb{C}^{N_{\text{tx}}/N_{\text{RF}}}$ | beamforming vector at the $r^{\text{th}}$ RF chain with $-45^\circ$ polarization |



# Hybrid Precoding with Subarray Structure

- The RF precoder is decomposed into a $+45^\circ$ polarized precoder $\widehat{\mathbf{F}}_{\text{RF}} \in \mathbb{C}^{N_{\text{tx}} \times N_{\text{RF}}}$ and a $-45^\circ$ polarized precoder $\widetilde{\mathbf{F}}_{\text{RF}} \in \mathbb{C}^{N_{\text{tx}} \times N_{\text{RF}}}$, i.e. $\mathbf{F}_{\text{RF}} := \left[\widehat{\mathbf{F}}_{\text{RF}}^\top \widetilde{\mathbf{F}}_{\text{RF}}^\top\right]$.
- The analog precoders $\widehat{\mathbf{F}}_{\text{RF}}$ and $\widetilde{\mathbf{F}}_{\text{RF}}$ take the form of a block diagonal matrix as follows:

$$\widehat{\mathbf{F}}_{\text{RF}} = \text{blkdiag}\left(\widehat{\mathbf{f}}_1, ..., \widehat{\mathbf{f}}_{N_{\text{RF}}}\right) = \begin{bmatrix} \widehat{\mathbf{f}}_1 & \dots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \dots & \widehat{\mathbf{f}}_{N_{\text{RF}}} \end{bmatrix} \quad \text{and} \quad \widetilde{\mathbf{F}}_{\text{RF}} = \text{blkdiag}\left(\widetilde{\mathbf{f}}_1, ..., \widetilde{\mathbf{f}}_{N_{\text{RF}}}\right) = \begin{bmatrix} \widetilde{\mathbf{f}}_1 & \dots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \dots & \widetilde{\mathbf{f}}_{N_{\text{RF}}} \end{bmatrix},$$

  where $(\forall r \in \{1, ..., N_{\text{RF}}\})\, \widehat{\mathbf{f}}_r, \widetilde{\mathbf{f}}_r \in \mathcal{C}$.
- The cross-polarized mmWave channel at subcarrier $\bar{k}$ is represented in block form as

$$\mathbf{H}\left[\bar{k}\right] = \begin{bmatrix} \mathbf{H}\left[\bar{k}\right]_{+45^\circ} & \mathbf{H}\left[\bar{k}\right]_{\pm 45^\circ} \\ \mathbf{H}\left[\bar{k}\right]_{\mp 45^\circ} & \mathbf{H}\left[\bar{k}\right]_{-45^\circ} \end{bmatrix},$$

  where the diagonal blocks $\mathbf{H}\left[\bar{k}\right]_{+45^\circ}$ and $\mathbf{H}\left[\bar{k}\right]_{-45^\circ}$ represent the co-polarized, and the off-diagonal blocks $\mathbf{H}\left[\bar{k}\right]_{\pm 45^\circ}$ and $\mathbf{H}\left[\bar{k}\right]_{\mp 45^\circ}$ represent the cross-polarized components.

# Problem Statement

- The received signal at subcarrier $\bar{k}$ for a transmitted symbol $\mathbf{s}\left[\bar{k}\right] \in \mathbb{C}^{N_s}$ is given by

$$\mathbf{y}\left[\bar{k}\right] = \mathbf{H}\left[\bar{k}\right]\mathbf{F}_{\mathsf{RF}}\mathbf{F}\left[\bar{k}\right]\mathbf{s}\left[\bar{k}\right] + \mathbf{n}\left[\bar{k}\right],$$

  where $\mathbf{n}\left[\bar{k}\right] \in \mathbb{C}^{2N_{\mathsf{rx}}}$ denotes the additive white Gaussian noise.
- With $\left(\forall \bar{k} \in \left\{1, \ldots, \bar{K}\right\}\right) \mathbf{s}\left[\bar{k}\right] \sim \mathcal{N}\left(\mathbf{0}, \mathbf{I}\right)$, a general approach for hybrid precoding is to maximize the mutual information given in **Problem 1**.

**Problem 1**

$$\left\{\mathbf{F}^{\star}_{\mathsf{RF}}, \left\{\mathbf{F}^{\star}\left[\bar{k}\right]\right\}_{\bar{k}=1}^{\bar{K}}\right\} \in \underset{\mathbf{F}_{\mathsf{RF}}, \left\{\mathbf{F}\left[\bar{k}\right]\right\}_{\bar{k}=1}^{\bar{K}}}{\arg\max} \sum_{\bar{k}=1}^{\bar{K}} \log_2 \left|\mathbf{I} + \rho\mathbf{H}\left[\bar{k}\right]\mathbf{F}_{\mathsf{RF}}\mathbf{F}\left[\bar{k}\right]\mathbf{F}^{H}\left[\bar{k}\right]\mathbf{F}_{\mathsf{RF}}^{H}\mathbf{H}^{H}\left[\bar{k}\right]\right|$$

$$\text{such that} \quad \mathbf{F}_{\mathsf{RF}} \in \left\{ \left[\widehat{\mathbf{F}}_{\mathsf{RF}}^{\top} \widetilde{\mathbf{F}}_{\mathsf{RF}}^{\top}\right]^{\top} \middle| \begin{array}{c} \widehat{\mathbf{F}}_{\mathsf{RF}} = \mathsf{blkdiag}\left(\widehat{\mathbf{f}}_1, \ldots, \widehat{\mathbf{f}}_{N_{\mathsf{RF}}}\right), \widetilde{\mathbf{F}}_{\mathsf{RF}} = \mathsf{blkdiag}\left(\widetilde{\mathbf{f}}_1, \ldots, \widetilde{\mathbf{f}}_{N_{\mathsf{RF}}}\right) \\ \text{and } \left(\forall r \in \left\{1, \ldots, N_{\mathsf{RF}}\right\}\right) \widehat{\mathbf{f}}_r, \widetilde{\mathbf{f}}_r \in \mathcal{C} \end{array} \right\},$$

$$\sum_{\bar{k}=1}^{\bar{K}} \left\|\mathbf{F}_{\mathsf{RF}}\mathbf{F}\left[\bar{k}\right]\right\|^2 = \bar{K}N_s.$$

- The design of the hybrid precoder in **Problem 1** is challenging due to
  - the nonconvex constraint on $\mathbf{F}_{\mathsf{RF}}$, and
  - the coupling between the analog and digital precoding matrices, i.e., $\sum_{\bar{k}=1}^{\bar{K}} \left\|\mathbf{F}_{\mathsf{RF}}\mathbf{F}\left[\bar{k}\right]\right\|^2 = \bar{K}N_s$.

# Analog Precoding

- **Problem 1** can be reduced to the following exhaustive search problem over the precoding matrices $\mathbf{F}_{\text{RF}}$ by decoupling the analog and digital precoders [3,4]:

**Problem 2**

$$\mathbf{F}^{\star}_{\text{RF}} \in \begin{array}{cl} \underset{\mathbf{F}_{\text{RF}}}{\arg\max} & \sum_{\bar{k}=1}^{\bar{K}} \log_2 \left| \mathbf{I} + \rho \mathbf{H}\left[\bar{k}\right] \mathbf{F}_{\text{RF}} \left( \mathbf{F}_{\text{RF}}^H \mathbf{F}_{\text{RF}} \right)^{-1} \mathbf{F}_{\text{RF}}^H \mathbf{H}^H \left[\bar{k}\right] \right| \\ \text{such that} & \mathbf{F}_{\text{RF}} \in \left\{ \left[ \widehat{\mathbf{F}}_{\text{RF}}^{\top} \widetilde{\mathbf{F}}_{\text{RF}}^{\top} \right]^{\top} \middle| \begin{array}{c} \widehat{\mathbf{F}}_{\text{RF}} = \text{blkdiag}\left( \widehat{\mathbf{f}}_1, \ldots, \widehat{\mathbf{f}}_{N_{\text{RF}}} \right), \widetilde{\mathbf{F}}_{\text{RF}} = \text{blkdiag}\left( \widetilde{\mathbf{f}}_1, \ldots, \widetilde{\mathbf{f}}_{N_{\text{RF}}} \right) \\ \text{and } (\forall r \in \{1, \ldots, N_{\text{RF}}\})\ \widehat{\mathbf{f}}_r, \widetilde{\mathbf{f}}_r \in \mathcal{C} \end{array} \right\}. \end{array}$$

- Solution to **Problem 2** is still hard due to non-convex constraints and large signalling overhead.

Note: Once the analog precoding matrix $\mathbf{F}^{\star}_{\text{RF}}$ is obtained, the best digital predcoder $\mathbf{F}^{\star}\left[\bar{k}\right]$, in the sense of maximizing **Problem 1**, can be computed as $\left(\forall \bar{k} \in \left\{1, \ldots, \bar{K}\right\}\right) \mathbf{F}^{\star}\left[\bar{k}\right] = f\left(\mathbf{F}^{\star}_{\text{RF}}\right)$ where $f : \mathbb{C}^{2N_{\text{tx}} \times N_{\text{RF}}} \to \mathbb{C}^{N_{\text{RF}} \times N_s}$ is a function given in [3,4].

[3] Alkhateeb, Ahmed, and Robert W. Heath. "Frequency Selective Hybrid Precoding for Limited Feedback Millimeter Wave Systems." IEEE Transactions on Communications 64.5 (2016): 1801-1818.

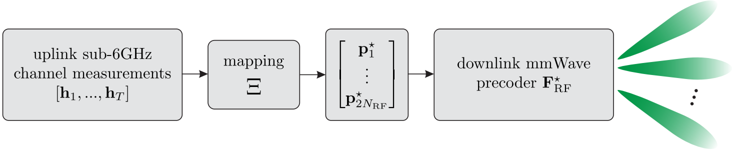
[4] Park, Sungwoo, Ahmed Alkhateeb, and Robert W. Heath. "Dynamic Subarrays for Hybrid Precoding in Wideband mmWave MIMO Systems." IEEE Transactions on Wireless Communications 16.5 (2017): 2907-2920.

# Mapping sub-6GHz Channels to mmWave Beams

- To cope with **Problem 2**, we assume that there exists an ideal mapping

$$\Xi : \mathbb{C}^{2N_{\text{tx}}^{\text{sub-6}} \times K \times T} \to \mathbb{R}^{2N_{\text{RF}}|\mathcal{C}|} : [\mathbf{h}_1, \dots, \mathbf{h}_T] \mapsto \left[\mathbf{p}_1^\star, \dots, \mathbf{p}_{2N_{\text{RF}}}^\star\right]^\top,$$

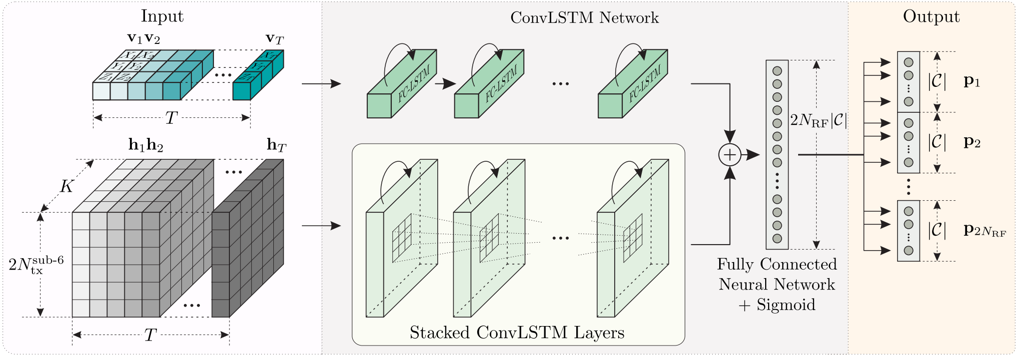
where $\mathbf{F}_{\text{RF}}^\star$ can be reconstructed from $\left[\mathbf{p}_1^\star, \dots, \mathbf{p}_{2N_{\text{RF}}}^\star\right]^\top$.




- The reconstruction of the precoder $\mathbf{F}_{\text{RF}}^\star = \left[\widehat{\mathbf{F}}_{\text{RF}}^{\star\top}\ \widetilde{\mathbf{F}}_{\text{RF}}^{\star\top}\right]^\top$ from $\left[\mathbf{p}_1^\star, \dots, \mathbf{p}_{2N_{\text{RF}}}^\star\right]^\top$ is performed as follows

$$\widehat{\mathbf{F}}_{\text{RF}}^\star = \text{blkdiag}\left(\widehat{\mathbf{f}}_1^\star, \dots, \widehat{\mathbf{f}}_{N_{\text{RF}}}^\star\right), (\forall r \in \{1, \dots, N_{\text{RF}}\}) \begin{array}{c} \widehat{\mathbf{f}}_r^\star = \mathbf{c}_{i_r^\star} \in \mathcal{C} \\ i_r^\star \in \underset{i=1,\dots,|\mathcal{C}|}{\text{arg max}} \left([\mathbf{p}_r^\star]_i\right) \end{array}, \quad \widetilde{\mathbf{F}}_{\text{RF}}^\star = \text{blkdiag}\left(\widetilde{\mathbf{f}}_1^\star, \dots, \widetilde{\mathbf{f}}_{N_{\text{RF}}}^\star\right), (\forall r \in \{1, \dots, N_{\text{RF}}\}) \begin{array}{c} \widetilde{\mathbf{f}}_r^\star = \mathbf{c}_{i_r^\star} \in \mathcal{C} \\ i_r^\star \in \underset{i=1,\dots,|\mathcal{C}|}{\text{arg max}} \left(\left[\mathbf{p}_{r+N_{\text{RF}}}^\star\right]_i\right) \end{array}.$$

# Proposed Neural Network Architecture

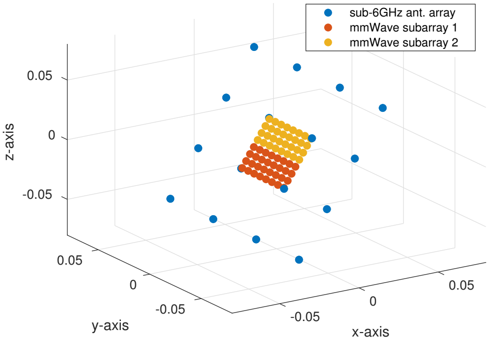



We train a neural network by trying to minimize the expected value of the binary cross entropy loss given by

$$l\left(\left[\mathbf{p}_1^\star, \ldots, \mathbf{p}_{2N_{\mathsf{RF}}}^\star\right]^\top, \left[\mathbf{p}_1, \ldots, \mathbf{p}_{2N_{\mathsf{RF}}}\right]^\top\right) = -\frac{1}{2N_{\mathsf{RF}}\,|\mathcal{C}|} \sum_{r=1}^{2N_{\mathsf{RF}}} \sum_{i=1}^{|\mathcal{C}|} \left( [\mathbf{p}_r^\star]_i \log\left([\mathbf{p}_r]_i\right) + \left(1 - [\mathbf{p}_r^\star]_i\right) \log\left([1 - \mathbf{p}_r]_i\right) \right).$$

# Simulation Parameters

| Parameter | Transceiver | |
|---|---|---|
| | sub-6GHz | mmWave |
| Carrier frequency [GHz] | 3.6 | 26 |
| Bandwidth [MHz] | 20 | 800 |
| OFDM subcarriers | $K = 32$ | $\bar{K} = 512$ |
| BS antenna size [UPA] | $4 \times 4$ | $8 \times 8$ |
| UE anetnna size | 1 | $2 \times 2$ UPA |
| Polarization | $\pm 45°$ | |
| Signal processing | Fully Digital | HBF with subarray structure ($N_{\mathrm{RF}} = 2$) codebook design [5] |
| Propagation scenario | 3GPP_38.901_UMa_NLOS [6] | |
| UE mobility | 30 km/h | |
| Training samples | $95 \cdot 10^3$ | |
| Test samples | $19 \cdot 10^3$ | |




[5] Xie, Yi, et al. "A Limited Feedback Scheme for 3D Multiuser MIMO based on Kronecker Product Codebook." 2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC). IEEE, 2013.
[6] S. Jaeckel, et al. "QuaDRiGa-Quasi Deterministic Radio Channel Generator, User Manual and Documentation," Fraunhofer Heinrich Hertz Institute, Tech. Rep. v1, pp. 4–1, 2016.

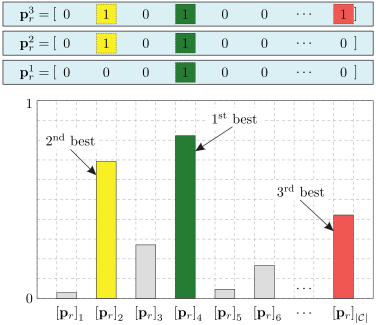
# Performance Evaluation

We introduce *best-n* prediction accuracy defined by

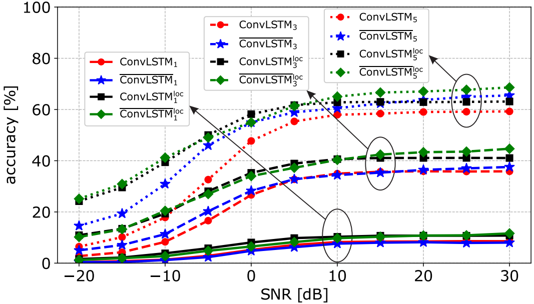
$$A_{\text{best-n}} = \frac{1}{S}\sum_{s=1}^{S} \mathbb{1}^{n}\Big(\big[\mathbf{p}_1^n,\dots,\mathbf{p}_{2N_{\text{RF}}}^n\big],\big[\mathbf{p}_1^\star,\dots,\mathbf{p}_{2N_{\text{RF}}}^\star\big]\Big),$$

where $S$ is the test dataset size, and $\mathbb{1}_{(\cdot,\cdot)}$ is the indicator function given by

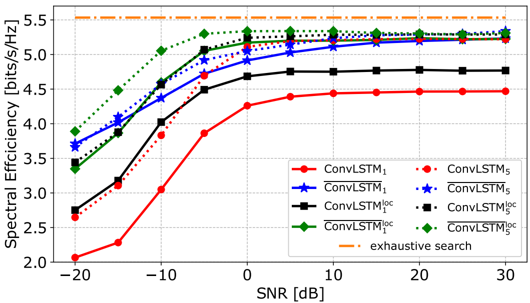
$$\mathbb{1}^{n}\Big(\big[\mathbf{p}_1^n,\dots,\mathbf{p}_{2N_{\text{RF}}}^n\big],\big[\mathbf{p}_1^\star,\dots,\mathbf{p}_{2N_{\text{RF}}}^\star\big]\Big) := \begin{cases} 1 & \text{, if } \sum_{r=1}^{2N_{\text{RF}}}\sum_{i=1}^{|\mathcal{C}|} [\mathbf{p}_r^n]_i\,[\mathbf{p}_r^\star]_i = 2N_{\text{RF}}, \\ 0 & \text{, otherwise.} \end{cases}$$



# Results




Prediction accuracy




Spectral efficiency

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