Some Aspects on Hybrid Wideband Transceiver Design for mmWave Communication Systems

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Introduction

- mmWave frequency ranges are considered to be a key enabler for extremely high throughput in 5G
- Principal issues to solve on the PHY layer: transmit/receive strategy, channel estimation/tracking, multi-user communication, waveform design, etc.
- Our focus: Broadband transceiver design in the hybrid beamforming architecture

Problem Description

Assuming perfect CSI, define the transmit and receive strategies for a multitap channel

Main issues:

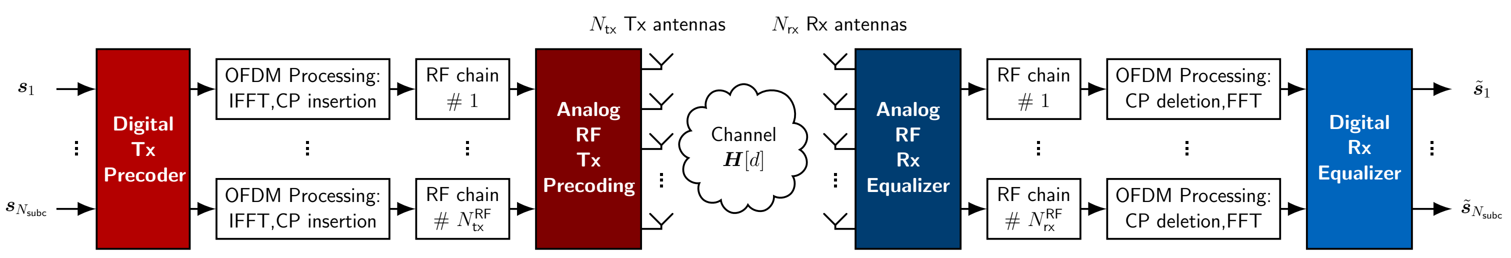
- For practical solutions, the analog beamformers $\boldsymbol{P}_{k,A}$ as well as combiners $\boldsymbol{G}_{k,A}$ are constant across the subcarriers
- Computational complexity of solutions

Relevant Work in the Literature

- Narrowband solutions
  - Exploiting channel spatial sparsity [a]
  - Exploiting estimated channel subspaces [b]
- Multicarrier solutions
  - Codebook-based approach with suboptimal solutions more efficient than the exhaustive search.[c]
  - Sequential searching algorithm with limited feedback assumption. [d]
  - Solution exploiting (slowly varying) second order statistics. [e]

[a] O. El Ayach et al. "Spatially Sparse Precoding in Millimeter Wave MIMO Systems"
[b] H. Ghauch et al. "Subspace Estimation and Decomposition for Hybrid Analog-Digital Millimetre-Wave MIMO systems"
[c] C. Kim et al. "Multi-beam transmission diversity with hybrid beamforming for MIMO-OFDM systems"
[d] A. Alkhateeb et al. "Frequency Selective Hybrid Precoding for Limited Feedback Millimeter Wave Systems"
[e] A. Adhikary et al. "Joint Spatial Division and Multiplexing for mm-Wave Channels"

System Model



$$\boldsymbol{H}_k = \frac{1}{\sqrt{N_{\text{subc}}}} \sum_{d=0}^{D-1} \boldsymbol{H}[d] \exp\left(\frac{j2\pi k}{N_{\text{subc}}} d\right)$$

$$\tilde{\boldsymbol{s}}_k = \boldsymbol{G}_{k,D}^{\text{H}} \boldsymbol{G}_{k,A}^{\text{H}} \boldsymbol{H}_k \boldsymbol{P}_{k,A} \boldsymbol{P}_{k,D} \boldsymbol{s}_k + \boldsymbol{G}_{k,D}^{\text{H}} \boldsymbol{G}_{k,A}^{\text{H}} \boldsymbol{\eta}_k$$

Channel Model

$$\boldsymbol{H}[d] = \beta \sqrt{\frac{N_{\text{rx}} N_{\text{tx}}}{L}} \sum_{l=1}^{N_{\text{cl}}} \sum_{r=1}^{N_{\text{path}}^{l}} \alpha_{r,l}\, p(dT_s - \tau_l - \tau_r) \boldsymbol{a}_{\text{rx}}(\boldsymbol{\theta}_{r,l}) \boldsymbol{a}_{\text{tx}}^{\text{H}}(\phi_{r,l})$$

Assumptions:

- The number of paths is significantly lower than for the sub-6GHz frequency band.
- The paths propagate in space and time clusters.

Proposed Solution

- Based on the perfect (or estimated) CSI, design optimal linear precoders and combiners
- Decompose the optimal precoding/combining matrices **jointly** for a set of subcarriers Ω, such that the analog components are equal for all the subcarriers in the set
- For the decomposition, use the (heuristic) objective of minimizing the Frobenius norm of the error matrix

Formal Description

$$\left(\boldsymbol{P}_{\Omega,A}^{\star}, \boldsymbol{P}_{\Omega,D}^{\star}\right) = \underset{\boldsymbol{P}_{\Omega,A}, \boldsymbol{P}_{\Omega,D}}{\arg\min} \quad \|\boldsymbol{P}_{\Omega}^{\star} - \boldsymbol{P}_{\Omega,A}\boldsymbol{P}_{\Omega,D}\|_{\text{F}}$$

$$\text{s.t.} \quad \|\boldsymbol{P}_{\Omega,A}\boldsymbol{P}_{\Omega,D}\|_{\text{F}}^2 \leq |\Omega| \frac{P_{\text{tx}}}{N_{\text{subc}}}, \quad \boldsymbol{P}_{\Omega,A} \in \mathcal{P}_{\mathcal{A}}$$

where

$$\boldsymbol{P}_{\Omega}^{\star} = \left[\boldsymbol{P}_{\omega_1}^{\star}, \ldots, \boldsymbol{P}_{\omega_{|\Omega|}}^{\star}\right] \in \mathbb{C}^{N_{\text{rx}} \times (|\Omega| N_{\text{s}})},$$

$$\boldsymbol{P}_{\Omega,D} = \left[\boldsymbol{P}_{\omega_1,D}, \ldots, \boldsymbol{P}_{\omega_{|\Omega|},D}\right] \in \mathbb{C}^{N_{\text{tx}}^{\text{RF}} \times (|\Omega| N_{\text{s}})},$$

$$\boldsymbol{P}_{\Omega,A} \in \mathbb{C}^{N_{\text{tx}} \times N_{\text{tx}}^{\text{RF}}}$$

$$\Omega \subset \{1, \ldots, N_{\text{subc}}\}$$

$$\omega_l \in \Omega,\ \forall l \in \{1, \ldots, |\Omega|\}$$

Solutions

Considered strategies:

- **Full digital setup.** Linear precoding with $\boldsymbol{P}_k^{\star}$ and linear combining with $\boldsymbol{G}_k^{\star}$ for each subcarrier k
- **Full hybrid transceiver.** Linear precoding with $\boldsymbol{P}_{k,A}^{\star}\boldsymbol{P}_{k,D}^{\star}$ and linear combining with $\left(\boldsymbol{G}_{k,A}^{\star}\boldsymbol{G}_{k,D}^{\star}\right)^{\text{H}}$ at each subcarrier.
- **Full hybrid transceiver.** Linear precoding with $\boldsymbol{P}_{\Omega,A}^{\star}\boldsymbol{P}_{k,D}^{\star}$ and linear combining with $\left(\boldsymbol{G}_{\Omega,A}^{\star}\boldsymbol{G}_{k,D}^{\star}\right)^{\text{H}}$ at each subcarrier.

For solving the optimization problem, we use either the *Orthogonal Matching Pursuit* (OMP) or the *Block Coordinate Descent* (BCD) algorithm

(Brief) Description of the Algorithms

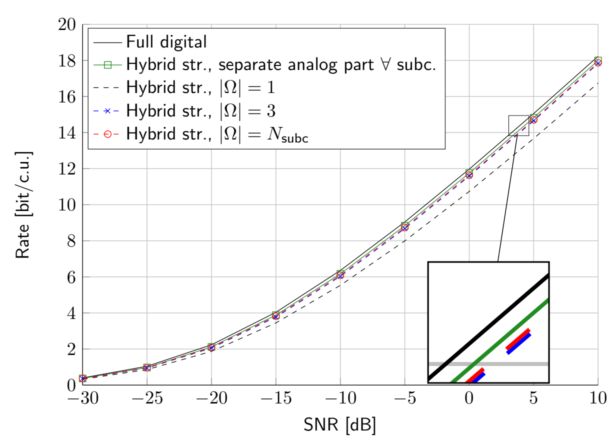
BCD:

- Optimize in each iteration either the digital or analog part. Assume the other one fixed
- In each step, project the analog matrix to the nearest (in Euclidean sense) matrix of the required set

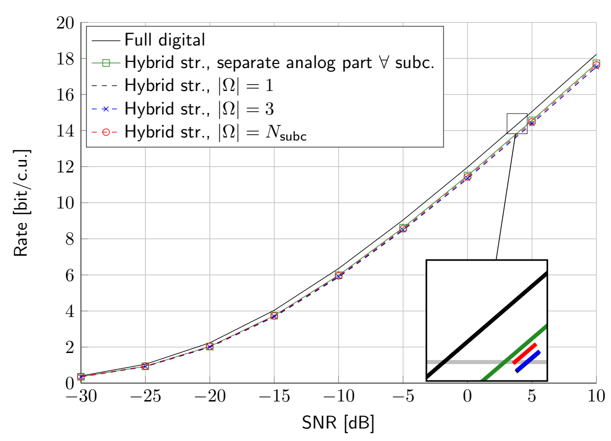
OMP:

- In each of the N_{RF} steps, choose a vector from the codebook that has the maximal projection on the remains of the matrix being decomposed.
- In each step, project out the selected vector

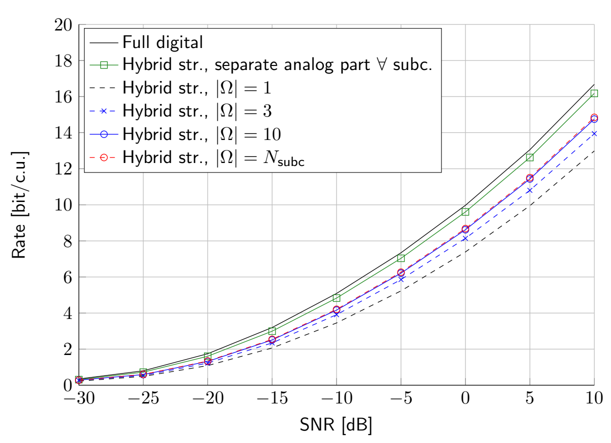
BCD Decomposition, Statistical Channel Model



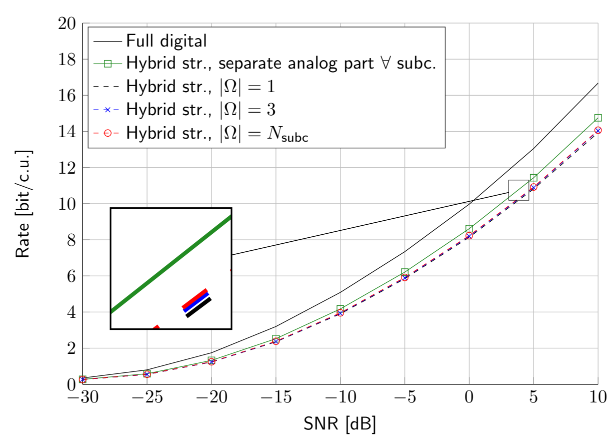
OMP Decomposition, Statistical Channel Model



BCD Decomposition, Measured Channels



OMP Decomposition, Measured Channels



Discussion

- A practical solution for wideband linear precoding/combining has been presented
- A reduced set of subcarriers can be used for designing the analog transmit/receive strategy → reduction of complexity
- The choice of the decomposition algorithm is remarkably important
- Future work should consider channel estimation

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