Wideband Hybrid Precoder for Massive MIMO Systems

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Background

- Massive MIMO

  High array gain， high throughput， low transmission power

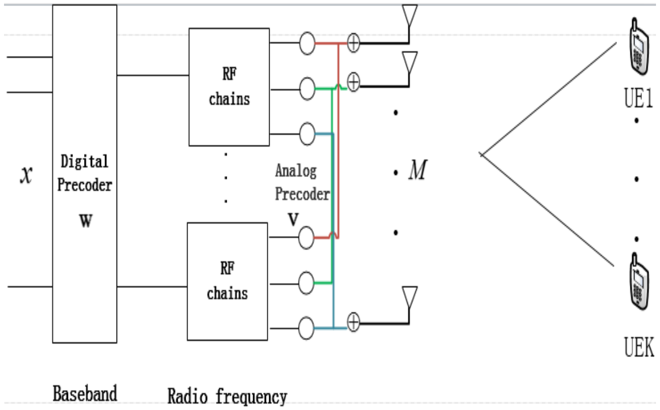
Full digital architecture

Excessive cost, complexity, and energy consumption

Hybrid architecture

Effectively reduce the number of RF chains

Analog precoder + Low-dimensional precoders



Hybrid architecture

Background

- Necessity of frequency-domain scheduling

Full digital architecture

Channel hardening; Plenty spatial degrees of freedom

Unnecessary!

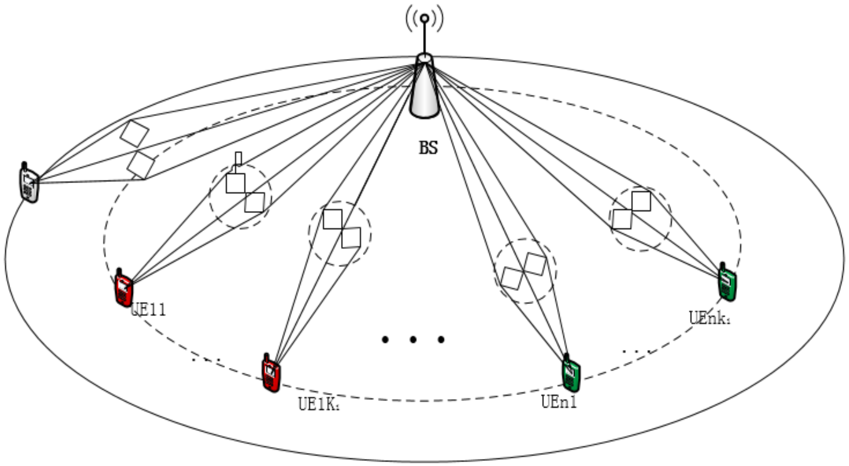
Hybrid architecture

Reduce the spatial degrees of freedom

Necessary!

BUT existing work on hybrid precoder mainly focus on single-subcarrier

System Model



Single-cell downlink SDMA-OFDMA massive MIMO system

M antennas ; *L* RF chains;

N resource blocks(RBs) ;

K users served *N* RBs

For data transmission，the received signal of the *k*-th user on the *n*-th RB（UE_{nk}）

$$y_{nk} = \mathbf{h}_{nk}^{H} \mathbf{V} \mathbf{w}_{nk} x_{nk} + \sum_{\substack{j \in \mathcal{K}_n \\ j \neq k}} \mathbf{h}_{nk}^{H} \mathbf{V} \mathbf{w}_{nj} x_{nj} + z_{nk}$$

Analog Precoder : $\mathbf{V}$

Digital Precoders : $\{\mathbf{w}_{nk}\}$

Set of UE_{nk} : $\{\mathcal{K}_n\}$

Problem Formulation

Maximize the sum rate of all served users subject to the maximal transmit power of the BS

Joint optimization

non-convex

$$\max_{\boxed{\mathbf{V},\{\mathbf{w}_{nk}\}}} \sum_{n=1}^{N} \sum_{k\in\mathcal{K}_n} \log\left(1+\mathrm{SINR}_{nk}\right)$$

$$s.t. \sum_{n=1}^{N} \sum_{k\in\mathcal{K}_n} \left|\mathbf{V}\mathbf{w}_{nk}\right|^2 \le P_{\max}$$

maximal transmit power of the BS

$$\left|\left[\mathbf{V}\right]_{ml}\right| = 1,\ m = 1,\ldots,M,\ l = 1,\ldots,L$$

Constant modulus

where

$$\mathrm{SINR}_{nk} = \frac{\left|\mathbf{h}_{nk}^{H}\mathbf{w}_{nk}\right|^2}{\sum_{j=1,j\ne k}^{K}\left|\mathbf{h}_{nk}^{H}\mathbf{w}_{nj}\right|^2 + \sigma_{nk}^2}$$

Difficulties:

Joint optimization

Wideband analog precoder

Precoder Design

IEEE GlobalSIP

Alternating Optimization Algorithm

First, omit the phase-only constraint

Equivalence between sum rate maximization problem and weighted sum mean square error (MSE) minimization problem

$$\min_{\mathbf{V},\{\mathbf{w}_{nk},t_{nk}\}} \sum_{n=1}^{N} \sum_{k\in\mathcal{K}_n} t_{nk}\epsilon_{nk} - \log\left(t_{nk}\right)$$

weight for the data of UE_{nk}

MSE

$$s.t. \sum_{n=1}^{N} \sum_{k\in\mathcal{K}_n} \left|\mathbf{V}\mathbf{w}_{nk}\right| \leq P_{\max}$$

where

$$\epsilon_{nk} = \sum_{j\in\mathcal{K}_n} \left|g_{nk}\mathbf{h}_{nk}^H\mathbf{V}\mathbf{w}_{nj}\right|^2 - 2\Re\left\{g_{nk}\mathbf{h}_{nk}^H\mathbf{V}\mathbf{w}_{nk}\right\} + \left|g_{nk}\right|^2\sigma_{nk}^2 + 1$$

the receive filter of UE_{nk}

convex for each individual variable of $\mathbf{V}$, $\mathbf{w}_{nk}$, t_{nk} and g_{nk} when given the others

Precoder Design

standard alternating optimization method

1.Intiatize $\mathbf{V}$ and $\left\{\mathbf{w}_{nk}\right\}$ that satisfy the power constraint

2.Calculate g_{nk}

3.Calculate ϵ_{nk} and t_{nk}

4.Digital precoder: $\mathbf{w}_{nk} = t_{nk} g_{nk}^{H} \left(\sum_{j \in \mathcal{K}_n} t_{nj} \left| g_{nj} \right|^2 \mathbf{V}^H \mathbf{h}_{nj} \mathbf{h}_{nj}^H \mathbf{V} + \lambda_{\omega} \mathbf{V}^H \mathbf{V} \right)^{-1} \mathbf{V}^H \mathbf{h}_{nk}$

the lagrangian multiplier

5.Analog precoder: $\mathbf{v} = \left(\sum_{n=1}^{N} \sum_{k \in \mathcal{K}_n} \left(t_{nk} \left| g_{nk} \right|^2 \sum_{j \in \mathcal{K}_n} \left(\mathbf{w}_{nj}^H \mathbf{w}_{nj} \right)^T \otimes \left(\mathbf{h}_{nk}^H \mathbf{h}_{nk} \right) + \lambda_{v} \left(\mathbf{w}_{nk} \mathbf{w}_{nk}^H \right)^T \otimes \mathbf{I} \right) \right)^{-1}$

$$\sum_{n=1}^{N} \sum_{k \in \mathcal{K}_n} t_{nk} g_{nk}^{H} \left(\mathbf{w}_{nk}^{H} \right)^T \otimes \mathbf{h}_{nk}$$

6. Repeat steps 2~5 until convergence

Alternating!

7.Update $$[\mathbf{V}]_{ml} \leftarrow \frac{[\mathbf{V}]_{ml}}{\left|[\mathbf{V}]_{ml}\right|}$$

Precoder Design

A low-complexity algorithm

First, omit the phase-only constraint

Decoupling

Optimize the analog precoder ——uplink-downlink duality theory

$$\max_{\mathbf{V}} \max_{\{\mathbf{D}_n\}} \sum_{n=1}^{N} \log\det\left(\mathbf{D}_n \bar{\mathbf{H}}_n^H \mathbf{V}\mathbf{V}^H \bar{\mathbf{H}}_n + \mathbf{I}\right)$$

sum capacity of the equivalent downlink channels $\mathbf{h}_{nk}^H \mathbf{V}$

$$s.t. \quad \sum_{n=1}^{N} \mathrm{Tr}\left(\mathbf{D}_n\right) \le P_{\max}$$

$$\mathbf{V}^H \mathbf{V} = \mathbf{I}$$

Proposition :
An analog precoding matrix with orthogonal columns is optimal for sum capacity maximization

$\{\mathbf{D}_n\}$: transmit power matrix of UE_{nk} in the dual uplink

Optimize digital precoders

Steps 2~4 of alternating optimization algorithm

Precoder Design

First find $\mathbf{D}_n$

By assuming a full digital system and the channels of all users are orthogonal

$$[\mathbf{D}_n]_{ii} = \left(\mu - \frac{\sigma^2_{n\mathcal{K}_{n(i)}}}{\left\|\mathbf{h}_{n\mathcal{K}_{n(i)}}\right\|^2}\right)^+$$

μ : the water-level variable that is chosen to ensure $\sum_{n=1}^{N} \mathrm{Tr}(\mathbf{D}_n) = P_{\max}$

Given $\mathbf{D}_n$ and , optimize $\mathbf{V}$

Semi-definite relaxation (SDR) method $\mathbf{V}\mathbf{V}^H = \mathbf{Q}$

$$\begin{aligned} \max_{\mathbf{V}} \ & \sum_{n=1}^{N} \log\det\left(\mathbf{D}_n \bar{\mathbf{H}}_n^H \mathbf{Q} \bar{\mathbf{H}}_n + \mathbf{I}\right) \\ s.t. \ & \mathrm{Tr}(\mathbf{Q}) = L \\ & \mathbf{Q} \succeq 0 \\ & \mathrm{rank}(\mathbf{Q}) = L \end{aligned}$$

$\mathbf{Q}$ is positive semi-definite

Employ the Gaussian randomization method to obtain the analog precoder $\mathbf{V}$

Update $[\mathbf{V}]_{ml} \leftarrow \frac{[\mathbf{V}]_{ml}}{\left|[\mathbf{V}]_{ml}\right|}$

Simulation results

- divide all RBs into *B* groups and schedule the same users for the RBs in each group
- *B*=1 : SDMA-OFDM *B*>1:SDMA-OFDMA

antennas	64
P_{max} of the BS	46 dBm
The cell radius	250 m
The path loss model	$35.3+37.6\log_{10}(d)$
SNR	10 dB

RBs	32
K	16
$\{\mathcal{K}_n\}$	8

Methods for comparing

“Random scheduling”： select users randomly for each group

“Greedy scheduling”： select users providing the maximal sum rate for each group

Channel Model

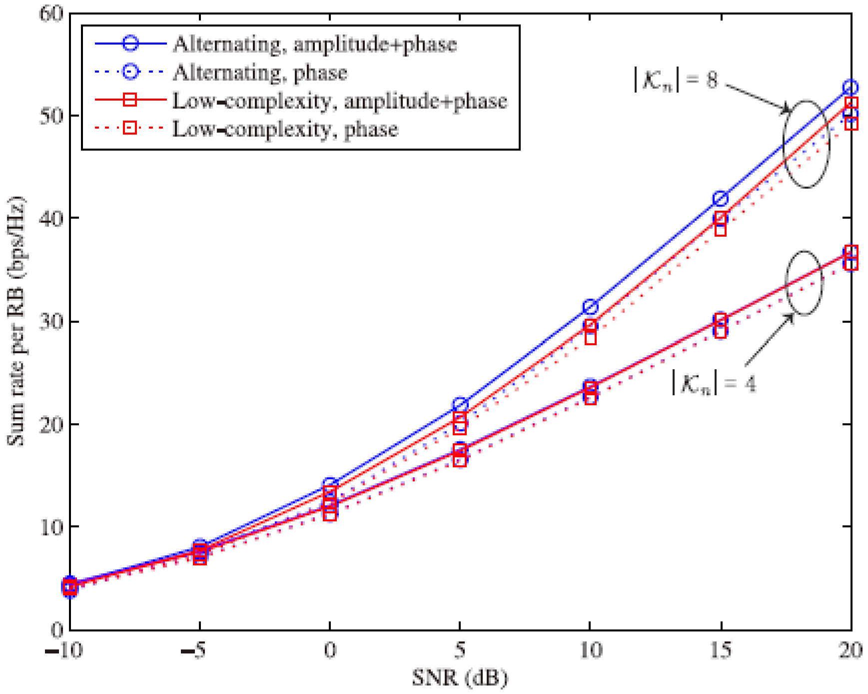
3GPP 36.873 UMa/NLOS

8×8 planar antenna array

elevation angle: $[-45^{\circ}, 45^{\circ}]$

azimuth angle: $[-60^{\circ}, 60^{\circ}]$

Simulation results



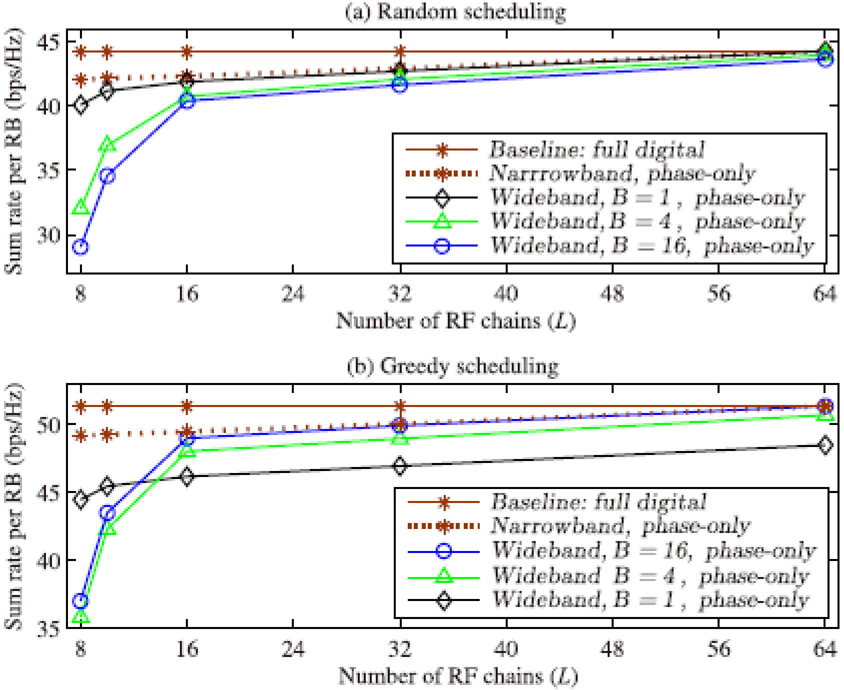
Performance comparison of the proposed algorithms

***L*=8**
B=16
Random scheduling

1. low-complexity algorithm performs close to the alternating optimization algorithm no matter when $|\mathcal{K}_n| = 4$ or $|\mathcal{K}_n| = 8$.

2. Phase only constraint on analog precoder leads to slight performance loss for both algorithms .

Simulation results



Impact of the number of RF chains and frequency-domain scheduling

Baseline: the per-RB performance of full digital precoder

1. “Random scheduling”:
   larger performance gap between “hybrid” and “full digital” in wideband systems;
   larger *B* , larger performance gap.

2. “Greedy scheduling”:
   Increasing *B* increases the multiuser diversity gain but reduces the array gain .

With greedy scheduling,the performance can be improved, when both *B* and *L* are large

Conclusions

- Optimized wideband hybrid precoder and investigated the necessity of frequency scheduling and the effectiveness of hybrid precoder in SDMA-OFDMA massive MIMO systems.

- Proposed a alternating optimization algorithm and an efficient non-iterative algorithm.

- Necessity of frequency scheduling and the effectiveness of wideband hybrid precoder depend on the employed scheduling method and the number of available RF chains

Thank you for your attention!