Thèse de Doctorat

Université de Limoges

Hybrid beamforming using massive antenna arrays for fixed sensor networks

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   - Beamforming
2. Hybrid Beamforming Fundamentals
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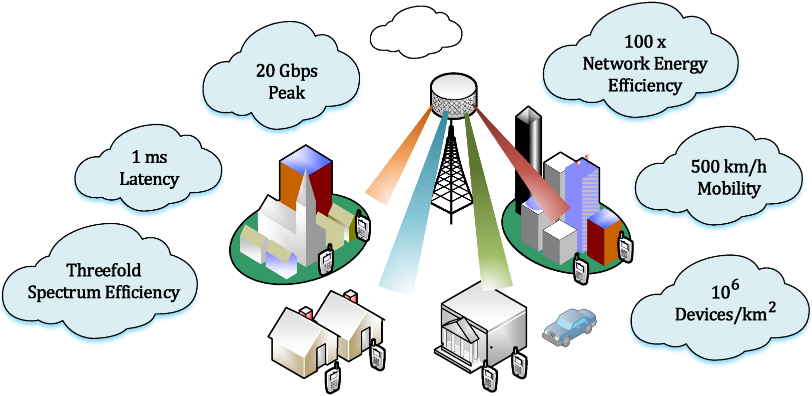
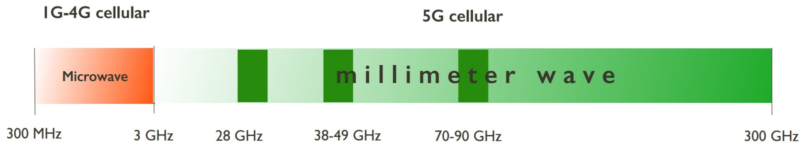
   - HBF Matrices Calculation: A New Approach
   - Hardware Implementation: Optimal Number of PSs
   - Mapping Strategy:A Machine Learning-Based Approach
   - Hybrid Beamforming for Wideband Channels
4. Conclusion and Perspectives

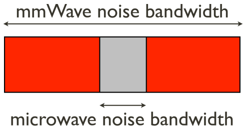
Motivation

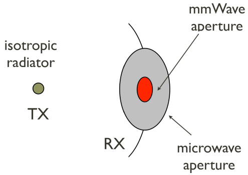

20 Gbps
Peak
100 x
Network Energy
Efficiency
1 ms
Latency
500 km/h
Mobility
Threefold
Spectrum Efficiency
10^6
Devices/km^2

Why Millimeter Wave?



- Abundance of Spectrum
- Larger Bandwidth and Signal-to-Noise Ratio (SNR)
- Smaller Wavelength and Captured Energy
- Exploiting Antenna Array Gain





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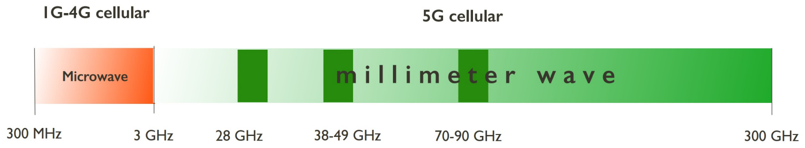

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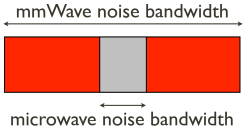
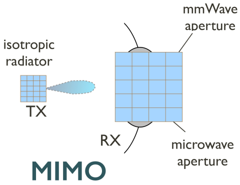
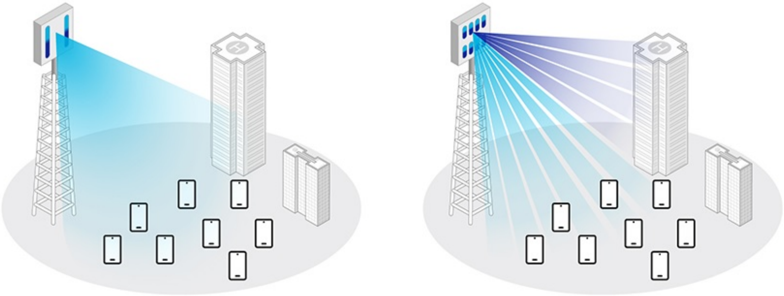


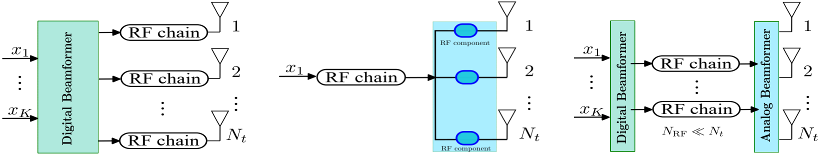


Massive MIMO

- **Increased Spectral Efficiency**:
  Simultaneous transmission and reception of multiple data streams.
- **Enhanced Signal Strength and Coverage**:
  Improved signal strength and coverage, even in challenging environments.
- **Expanded Connectivity**:
  Support for a larger number of concurrent users and devices.
- **Improved Energy Efficiency**:
  Efficient beamforming and reduced interference for optimized energy consumption.



Beamforming for mmWave Massive MIMO Systems



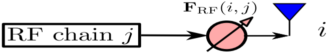
(a) Digital beamforming (b) Analog beamforming (c) Hybrid beamforming

- **Digital Beamforming (DBF)**
  - Precise control over beamforming weights.
  - Requires a dedicated RF chain per antenna; high hardware complexity, high cost and power consumption.
- **Analog Beamforming (ABF)**
  - Requires a shared RF chain; supports single-stream transmission.
  - Implemented using phase shifters; control signal's phase.
- **Hybrid Beamforming (HBF)**
  - Combines DBF and ABF; balance between performance and complexity
  - Requires $N_{RF} \ll N_t$ RF chains; supports multi-stream transmission.

Challenges

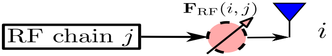
1. **Hardware complexity**
   - The number of RF chains
   - The analog network's complexity
     - The hardware implementation
     - The mapping strategy
2. **Computational complexity**
   - The algorithm's complexity in obtaining both Beamforming matrices, i.e., $\mathbf{F}_{\mathrm{BB}}$, and $\mathbf{F}_{\mathrm{RF}}$
3. **Spectral efficiency**
   - Spectral efficiency is a key performance indicator for any communication system

The Hardware Implementation



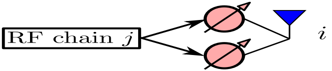
(a) **Single phase shifter**

$$\mathbf{F}_{\mathrm{RF}}(i,j) = e^{\jmath\theta} \qquad \theta \in [0,\ 2\pi)$$



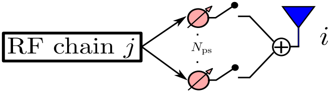
(b) **Quantized phase shifter**

$$\mathbf{F}_{\mathrm{RF}}(i,j) \in \left\{0, e^{\jmath 2\pi \frac{1}{N_{ps}}}, \ldots, e^{\jmath 2\pi \frac{N_{ps}-1}{N_{ps}}}\right\}$$



(c) **Double phase shifter**

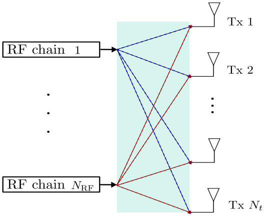
$$\mathbf{F}_{\mathrm{RF}}(i,j) = e^{\jmath\theta_1} + e^{\jmath\theta_2} \qquad \theta_1, \theta_2 \in [0,\ 2\pi)$$



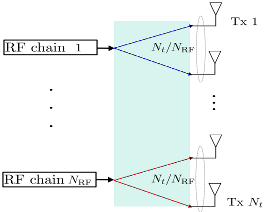
(d) **Fixed phase shifters**

$$\mathbf{F}_{\mathrm{RF}}(i,j) = \sum_{n=1}^{N_{\mathrm{ps}}} s_n e^{\jmath\theta_n} \qquad \theta_n = e^{\jmath 2\pi n/N_{\mathrm{ps}}}$$

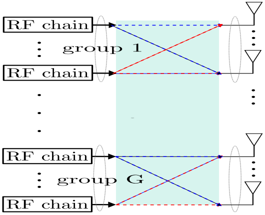
The Mapping Strategy



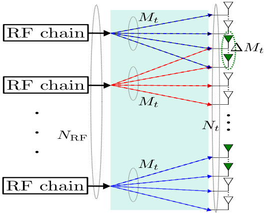
(a) **Fully-Connected (FC)**



(b) **Partially-Connected (PC)**



(c) **Group Connected (GC)**



(d) **Overlapped Subarray (OSA)**

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- HBF Matrices Calculation: A New Approach
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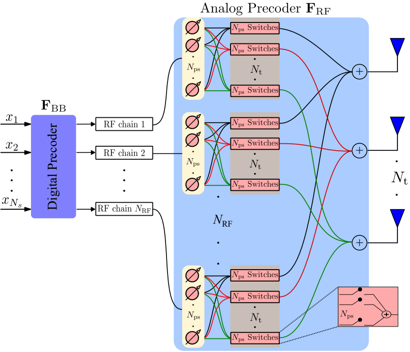
System Model

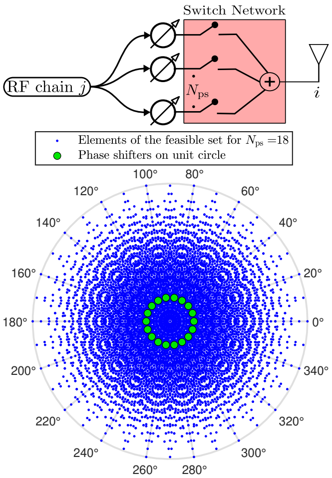


- Hardware implementation: fixed phase shifter
- Mapping strategy: fully-connected strategy
- The number of RF chains: minimum number
- The number of PSs is N_{ps} for each RF chain.
- PSs outputs are shared
- The received signal

$$\mathbf{y} = \sqrt{\rho}\mathbf{H}\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}\mathbf{x} + \mathbf{n}$$

J. Beiranvand et al, "An Efficient Low-Complexity Method to Calculate Hybrid Beamforming Matrices for mmWave Massive MIMO Systems," in *IEEE Open Journal of the Communications Society*, vol. 2, pp. 1239-1248, 2021, doi: 10.1109/OJCOMS.2021.3084343.

Analog beamforming coefficients



- $\mathbf{F}_{\mathrm{RF}}(i,j) = \mathbf{s}_{ij}\mathbf{c}$
- The vector $\mathbf{c} = \left[1, e^{\jmath 2\pi \frac{1}{N_{\mathrm{ps}}}}, \ldots, e^{\jmath 2\pi \frac{N_{\mathrm{ps}}-1}{N_{\mathrm{ps}}}}\right]^{\mathrm{T}}$ represents the phase shift vector.
- The binary vector $\mathbf{s}_{ij}$ represents switch states
- $2^{N_{\mathrm{ps}}}$ switch combinations generate beamforming coefficients (see the scatter plot)
- The analog precoder $\mathbf{F}_{\mathrm{RF}} = \mathbf{SC}$

$$\mathbf{S} \triangleq \begin{bmatrix} \mathbf{s}_{11} & \mathbf{s}_{12} & \cdots & \mathbf{s}_{1N_{\mathrm{s}}} \\ \vdots & & \ddots & \vdots \\ \mathbf{s}_{N_{\mathrm{t}}1} & \mathbf{s}_{N_{\mathrm{t}}2} & \cdots & \mathbf{s}_{N_{\mathrm{t}}N_{\mathrm{s}}} \end{bmatrix}_{N_{\mathrm{t}} \times N_{\mathrm{RF}} N_{\mathrm{ps}}}$$

$$\mathbf{C} \triangleq \begin{bmatrix} \mathbf{c} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{c} & & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{c} \end{bmatrix}_{N_{\mathrm{RF}} N_{\mathrm{ps}} \times N_{\mathrm{RF}}},$$

Problem Formulation

- The precoder design problem can be written as:

$$
\begin{aligned}
\left(\mathbf{S}^{\mathrm{opt}}, \mathbf{F}_{\mathrm{BB}}^{\mathrm{opt}}\right) = \underset{\mathbf{S}, \mathbf{F}_{\mathrm{BB}}}{\operatorname{argmin}} \quad & \left\|\mathbf{F}_{\mathrm{opt}} - \mathbf{S}\mathbf{C}\mathbf{F}_{\mathrm{BB}}\right\|_{\mathrm{F}}^{2} \\
\text{s.t.} \quad & \left\|\mathbf{S}\mathbf{C}\mathbf{F}_{\mathrm{BB}}\right\|_{\mathrm{F}}^{2} = 1 \\
& \mathbf{S}\left(i, \ell\right) \in \{0, 1\}, \quad \forall i, \ell.
\end{aligned}
$$

- The matrix $\mathbf{F}_{\mathrm{opt}}$ is the optimal fully-digital precoder
- The binary matix $\mathbf{S} \in \mathbb{Z}_2^{N_{\mathrm{t}} \times N_{\mathrm{RF}} N_{\mathrm{ps}}}$, where $\mathbb{Z}_2 = \{0, 1\}$.
- The optimal solution is obtained through an exhaustive search
- The exhaustive search on the switch matrix $\mathbf{S}$ is infeasible

  For example with 256 antennas, 10 RF chains, and 16 phase shifters, the size of the search space is $2^{256 \times 10 \times 16} \approx \infty$

Decompose the optimization problem

- Assume $\mathbf{F}_{\mathrm{BB}} = \mathbf{I}_{N_{\mathrm{s}}}$ and $\mathbf{F}_{\mathrm{optn}} = \gamma \mathbf{F}_{\mathrm{opt}}$
- Under these assumptions:

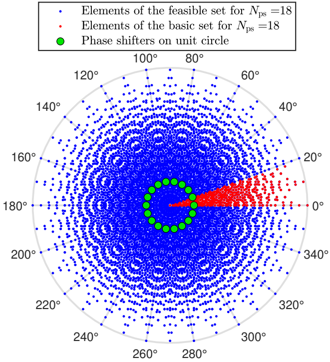
$$\begin{aligned} \mathbf{S}^{*} = \underset{\mathbf{S}}{\operatorname{argmin}} \quad & \left\| \mathbf{F}_{\mathrm{optn}} - \mathbf{S}\mathbf{C} \right\|_{\mathrm{F}}^{2} \\ \text{s.t.} \quad & \mathbf{S}(i,\ell) \in \{0,1\}, \quad \forall i,\ell, \end{aligned}$$

- As a result, the problem is decomposed into $N_{\mathrm{t}} N_{\mathrm{s}}$ independent sub-problems

$$\begin{aligned} \mathbf{s}_{ij} = \underset{\mathbf{s}_{ij}}{\operatorname{argmin}} \quad & \left| \mathbf{F}_{\mathrm{optn}}(i,j) - \mathbf{s}_{ij}\mathbf{c} \right|^{2} \\ \text{s.t.} \quad & \mathbf{s}_{ij}(\ell) \in \{0,1\}, \quad \forall \ell. \end{aligned}$$

- $\mathbf{s}_{ij}\mathbf{c}$ generates a feasible set $\mathcal{F}$ with maximum size of $2^{N_{\mathrm{ps}}}$
- The size of the feasible set $\mathcal{F}$ is independent of the number of antennas and RF chains
- The exhaustive search is tractable even in a massive MIMO system.

Periodic property



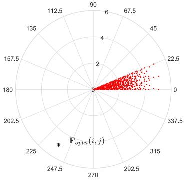
- The feasible set is created by N_{ps} periods of a basic sector
- The points in the basic sector form a basic set (red points) $\mathcal{F}^b_{N_{\text{ps}}}$
- The size of the search space is reduced N_{ps} times, i.e., $|\mathcal{F}^b_{N_{\text{ps}}}| = |\mathcal{F}_{N_{\text{ps}}}|/N_{\text{ps}}$
- Exploit the property to reduce computational complexity.

Using the basic set to find switch states

- Scaling the beamforming coefficient within the feasible circle
- Transfering the beamforming coefficient within the basic sector

$$\mathbf{M}(i,j) = \left\lfloor \frac{\measuredangle \mathbf{F}_{\text{optn}}(i,j)}{2\pi/N_{\text{ps}}} \right\rfloor$$

- Finding the nearest point in the basic sector
- Extracting the corresponding switch states
  $\tilde{\mathbf{s}}_{ij} = [0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]$
- Shifting the corresponding switch states
  $\mathbf{s}_{ij} = [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1]$



(a) (b) (c) (d)

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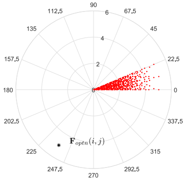
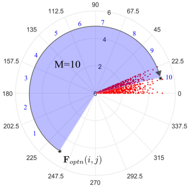


(a)



(b)

(c)

(d)

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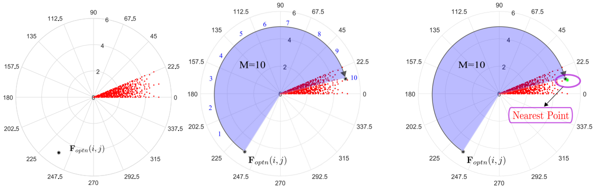

(a) (b) (c) (d)

Using the basic set to find switch states

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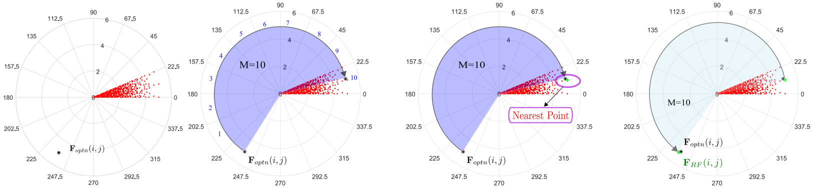


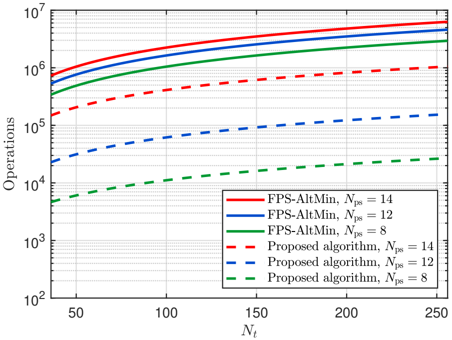
(a) (b) (c) (d)

Algorithm 1 A Low-Complexity Algorithm for Hybrid Systems

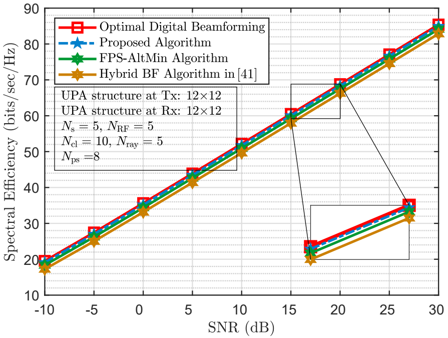
Require: $\mathbf{F}_{\text{opt}}$;

Compute $\mathbf{F}_{\text{optn}} = \gamma \mathbf{F}_{\text{opt}}$;
Obtain the matrix $\mathbf{M}$;
Transfer $\mathbf{F}_{\text{optn}}$ into the basic sector and obtain $\mathbf{F}_{\text{s}}$;
For $i = 1, \ldots, N_{\text{t}}$ and $j = 1, \ldots, N_{\text{s}}$;
    Find the nearest point of the basic set to $\mathbf{F}_{\text{s}}(i,j)$, $\mathbf{F}_{\text{s}}(i,j) \longmapsto \mathbf{F}_{\text{m}}(i,j)$;
    Extract $\widetilde{\mathbf{s}}_{ij}$ corresponds $\mathbf{F}_{\text{m}}(i,j)$ from the code book of $\mathcal{F}^{b}_{N_{\text{ps}}}$;
    Compute $\mathbf{s}_{ij}$ by $\mathbf{M}(i,j)$ circular right-shifts of $\widetilde{\mathbf{s}}_{ij}$;
    Calculate $\mathbf{F}_{\text{RF}}(i,j) = \mathbf{s}_{ij}\mathbf{c}$;
End for
$\widehat{\mathbf{F}}_{\text{BB}} = \left(\mathbf{F}^{\text{H}}_{\text{RF}} \mathbf{F}_{\text{RF}}\right)^{-1} \mathbf{F}^{\text{H}}_{\text{RF}} \mathbf{F}_{\text{opt}}$;
$\mathbf{F}_{\text{BB}} = \dfrac{\widehat{\mathbf{F}}_{\text{BB}}}{\left\| \mathbf{F}_{\text{RF}} \widehat{\mathbf{F}}_{\text{BB}} \right\|_{\text{F}}}$.

Numerical results



Computational complexity



Spectral efficiency

FPS-AltMin algorithm [45]

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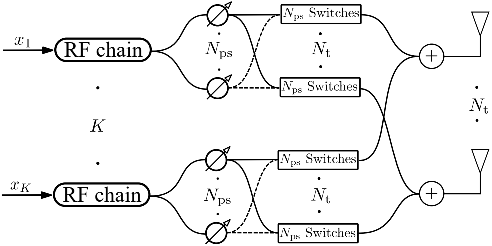
System Model

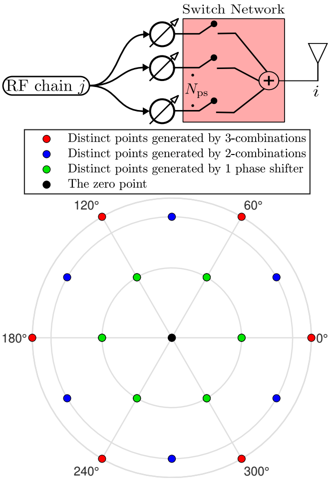


- Hardware implementation: fixed phase shifter
- Mapping strategy: fully-connected strategy
- With digital beamforming set as the identity matrix; focus on the impact of the number of phase shifters on the system's performance.
- The received signal

$$\mathbf{y} = \sqrt{\rho}\mathbf{H}\mathbf{F}_{\mathrm{RF}}\mathbf{x} + \mathbf{n},$$

J. Beiranvand et al, "How Many Fixed Phase Shifters Are Needed in a Hybrid BF Structure?," *ICC 2022 - IEEE International Conference on Communications*, Seoul, Korea, Republic of, 2022, pp. 444-449, doi: 10.1109/ICC45855.2022.9838503.

superposed points in the complete set



- The complete set, denoted as $\mathcal{S}_{N_{\text{ps}}}$, consists of all the generated outputs of switch combinations.
- Some of these points are superposed.
- The distinct points form the feasible set $\mathcal{F}_{N_{\text{ps}}}$
- For example, with $N_{\text{ps}} = 6$
  $|\mathcal{F}_6| = 19$ and $|\mathcal{S}_6| = 64$
- The distinct points are the ones that truly impact beamforming performance.
- We analyze the number of distinct points

The complete set $\mathcal{S}_{N_{\text{ps}}}$ vs the feasible set $\mathcal{F}_{N_{\text{ps}}}$

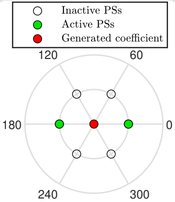
- The complete set $\mathcal{S}_{N_{\text{ps}}}$ can be express as:

$$\sum_{m \in \mathcal{A}_i} P_m \in \mathcal{S}_{N_{\text{ps}}} \quad \forall i = 1, \ldots, 2^{N_{\text{ps}}},$$

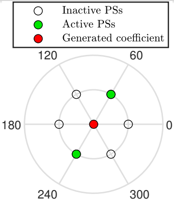
- $\mathcal{A}_i$ is a set representing the ith switch combination, and $P_m = e^{\jmath \frac{2\pi}{N_{\text{ps}}}(m-1)}$
- There are two reasons for superposed points;
  - **Zero-summation set (ZSS)**: which adds up to zero, $\mathcal{S}_{N_{\text{ps}}}$ i.e., $\sum_{m \in \mathcal{X}_{N_{\text{ps}},p}} P_m = 0$
  - **Subset of ZSS (SZSS)**: which adds up to non-zero, $\mathcal{S}_{N_{\text{ps}}}$ i.e., $\sum_{m \in \mathcal{R}_{N_{\text{ps}},p}} P_m = \sum_{m \in \bar{\mathcal{B}}_{N_{\text{ps}},p}} P_m \neq 0$
- We express the size of the feasible set as:

$$\left|\mathcal{F}_{N_{\text{ps}}}\right| = \sum_{n=0}^{\xi_{N_{\text{ps}}}-1} \binom{N_{\text{ps}}}{n} - \underbrace{\mathcal{Z}_{N_{\text{ps}}}(n)}_{ZSS} - \underbrace{\mathcal{Q}_{N_{\text{ps}}}(n)}_{SZSS}$$

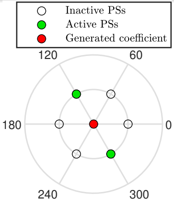
Zero-Summation Sets



(a) $X^1_{6,3} = \{1, 4\}$

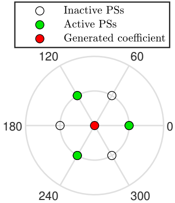


(b) $X^1_{6,3} = \{2, 5\}$

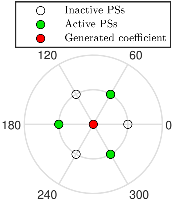


(c) $X^1_{6,3} = \{3, 6\}$

- Consider $\mathcal{X}_{N_{\text{ps}},p}$ composed of p elements
- p is a prime factor of N_{ps}
- For a given pair (N_{ps}, p), there are N_{ps}/p different ZSSs



(d) $X^1_{6,2} = \{1, 3, 5\}$



(e) $X^2_{6,2} = \{2, 4, 6\}$

Subset of Zero-Summation Set

- Consider $\mathcal{X}_{N_{\text{ps}},p}$ and $\bar{\mathcal{X}}_{N_{\text{ps}},p}$
- Two subsets $\mathcal{R}_{N_{\text{ps}},p}$ and $\mathcal{B}_{N_{\text{ps}},p}$ of $\mathcal{X}_{N_{\text{ps}},p}$

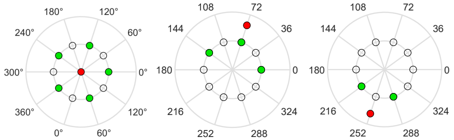
$$\sum_{m\in\mathcal{B}_{N_{\text{ps}},p}} P_m + \sum_{m\in\mathcal{R}_{N_{\text{ps}},p}} P_m = 0.$$

- Likewise, $\bar{\mathcal{B}}_{N_{\text{ps}},p}$ and $\bar{\mathcal{R}}_{N_{\text{ps}},p}$

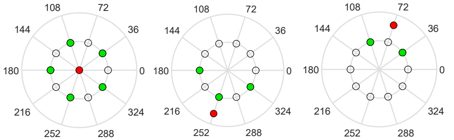
$$\sum_{m\in\bar{\mathcal{B}}_{N_{\text{ps}},p}} P_m + \sum_{m\in\bar{\mathcal{R}}_{N_{\text{ps}},p}} P_m = 0,$$

- We can see that

$$\sum_{m\in\mathcal{B}_{N_{\text{ps}},p}} P_m + \sum_{m\in\bar{\mathcal{B}}_{N_{\text{ps}},p}} P_m = 0$$



(a) $X_{10,5} = \{1, 3, 5, 7, 9\}$ (b) $\mathcal{R}_{10,5} = \{1, 3, 5\}$ (c) $\mathcal{B}_{10,5} = \{7, 9\}$

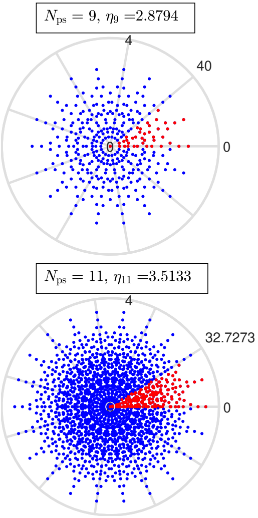


(d) $\bar{X}_{10,5} = \{2, 4, 6, 8, 10\}$ (e) $\bar{\mathcal{R}}_{10,5} = \{6, 8, 10\}$ (f) $\bar{\mathcal{B}}_{10,5} = \{2, 4\}$

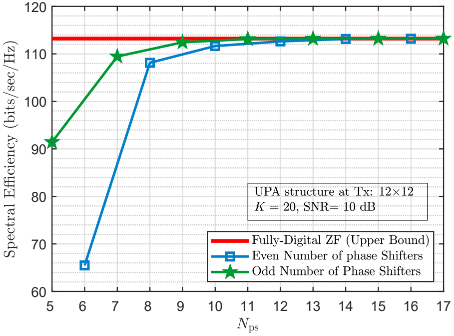
Characteristics of the system as a function of N_{ps}

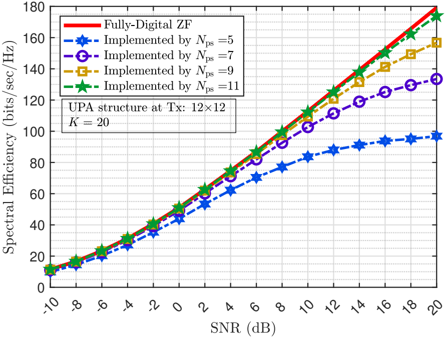
N_{ps}	$\xi_{N_{\text{ps}}}$	$\eta_{N_{\text{ps}}}$	$\lvert\mathcal{F}_{N_{\text{ps}}}\rvert$	$\lvert\mathcal{F}^b_{N_{\text{ps}}}\rvert$	$\mathcal{E}_{N_{\text{ps}}} \times 10^2$	$\frac{\lvert\mathcal{F}_{N_{\text{ps}}}\rvert}{\lvert\mathcal{S}_{N_{\text{ps}}}\rvert}$
2	2	1	3	2	33.97	75.00%
3	3	1	7	3	13.48	87.50%
4	3	1.4142	9	3	10.87	56.25%
5	5	1.6180	31	7	4.34	96.88%
6	4	2	19	4	6.68	29.69%
7	7	2.2470	127	19	2.07	99.22%
8	5	2.6131	81	11	2.60	31.64%
9	7	2.8794	343	39	1.19	66.99 %
10	6	3.2361	211	22	1.46	20.61%
11	11	3.5133	2047	187	0.69	99.95%
12	7	3.8637	361	31	1.05	08.81%
13	13	4.1481	8191	631	0.46	99.99%
14	8	4.4940	2059	148	0.58	12.57%
15	11	4.7834	16081	1073	0.34	49.08%
16	9	5.1258	6561	411	0.41	10.01%
17	17	5.4190	131071	7711	0.26	100.00%

As examples, the feasible set for $N_{ps} = 9, 10, 11$, and 12



Numerical results





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- HBF Matrices Calculation: A New Approach
- Hardware Implementation: Optimal Number of PSs
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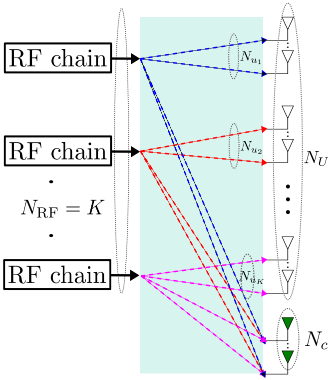
- Hybrid Beamforming for Wideband Channels

4 Conclusion and Perspectives

Partially/Fully-Connected Mapping Strategy



- N_{u_k} single-connected antennas (SCAs) are assined for the kth user.
- N_c fully-connected antennas (FCAs) are common for all users
- Controlling user priority by assigning more or fewer SCAs to a specific user.
- $N_c = 0$ converges to partially-connected strategy
- $N_c = N_t$ converges to fully-connected strategy
- Allowing to adjust the number of RF paths in $N_t + 1$ different levels
- Shaping a simple precoder matrix suitable for analytical optimization.

J. Beiranvand et al, "An Efficient Beamforming Architecture to Handle the Trade-Off Between Performance and Hardware Complexity in Multiuser Massive MISO Systems," in *IEEE Access*, vol. 10, pp. 132853-132862, 2022, doi: 10.1109/ACCESS.2022.3230326.

Partially/Fully-Connected Mapping Strategy

- The analog precoder and channel matrix can be expressed as

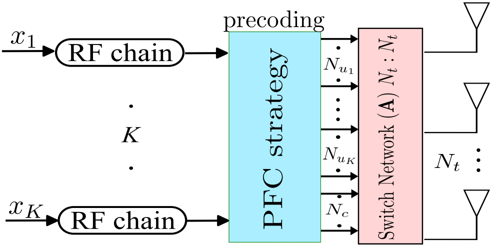
$$\mathbf{F} = \begin{bmatrix} \mathbf{f}_{\mathrm{u}_1} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{f}_{\mathrm{u}_2} & \dots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{f}_{\mathrm{u}_K} \\ \mathbf{f}_{\mathrm{c}_1} & \mathbf{f}_{\mathrm{c}_2} & \dots & \mathbf{f}_{\mathrm{c}_K} \end{bmatrix}, \qquad \mathbf{H} = \left[\mathbf{H}_{\mathcal{U}_1}, \mathbf{H}_{\mathcal{U}_2}, \dots, \mathbf{H}_{\mathcal{U}_K}, \mathbf{H}_{\mathcal{C}}\right],$$

- Based on the ZF precoder, non-zero coefficients in the kth column can be obtained from:

$$\widehat{\mathbf{f}}_k = \mathbf{H}_k^{\mathrm{H}} \left(\mathbf{H}_k \mathbf{H}_k^{\mathrm{H}}\right)^{-1} \mathbf{i}_k,$$

- $\widehat{\mathbf{f}}_k = \left[\mathbf{f}_{\mathrm{u}_k}^{\mathrm{T}}, \mathbf{f}_{\mathrm{c}_k}^{\mathrm{T}}\right]$, $\mathbf{H}_k = \left[\mathbf{H}_{\mathcal{U}_k} | \mathbf{H}_{\mathcal{C}}\right]$,
- $\mathbf{i}_k$ is the kth column of the matrix $\mathbf{I}_K$

Dynamic Partially/Fully-Connected Strategy



- Dynamic PFC strategy allows us to select FCAs and assign SCAs to users
- Dynamic PFC strategy adapts the RF paths through the switch network $\mathbf{A}$
- It can be mathematically represented by

$$\mathbf{y} = \sqrt{\rho}\mathbf{H}\mathbf{A}\mathbf{F}\mathbf{x} + \mathbf{n}.$$

- $\mathbf{A}$ is a permutation matrix of size $N_t \times N_t$

Dynamic Partially/Fully-Connected Strategy

Example; 8 antennas, 2 users

- $\mathcal{U}_1 = \{1, 4, 8\}$
- $\mathcal{U}_2 = \{2, 5, 7\}$
- $\mathcal{C} = \{3, 6\}$

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}_{8\times 8}$$

- The objective function can be written as:

$$\left(\mathcal{C}^{opt}, \mathcal{U}_1^{opt}, \dots, \mathcal{U}_K^{opt}\right) = \underset{\mathcal{C}, \mathcal{U}_1, \dots, \mathcal{U}_K}{\operatorname{argmin}} \sum_{k=1}^{K} \left[\left(\mathbf{H}_k \mathbf{H}_k^{\mathrm{H}}\right)^{-1}\right]_{k,k}.$$

- Exploring all possible combinations of antenna allocation is impractical.
- We propose two algorithms to select FCAs and assign SCAs to users.

Dynamic Partially/Fully-Connected Strategy

Example; 8 antennas, 2 users

- $\mathcal{U}_1 = \{1, 4, 8\}$
- $\mathcal{U}_2 = \{2, 5, 7\}$
- $\mathcal{C} = \{3, 6\}$

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}_{8\times 8}$$

- The objective function can be written as:

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- Exploring all possible combinations of antenna allocation is impractical.
- We propose two algorithms to select FCAs and assign SCAs to users.

Algorithm 2 Selecting FCAs

- As FCAs perform the majority of beamforming, selecting the FCAs is prioritize
- The problem of selecting FCAs can be formulated as a combinatorial column selection problem as:

$$\mathcal{C} = \underset{\mathcal{C}}{\operatorname{argmin}} \quad \operatorname{Tr}\left\{\left(\mathbf{H}_{\mathcal{C}}\mathbf{H}_{\mathcal{C}}^{\mathrm{H}}\right)^{-1}\right\}$$

- To solve this problem, we adopt a greedy removal method [70].

Require: $\mathbf{H}$, N_c;
1: $\mathcal{C}^{(0)} = \{\ell \in \mathbb{N} : \ell \leq N_\mathrm{t}\}$;
2: **For** $t = 1, \ldots, N_\mathrm{t} - N_\mathrm{c}$
3: $\quad \ell = \operatorname{argmin}_{\ell} \quad \operatorname{Tr}\left\{\left(\mathbf{H}_{\mathcal{C}^{(t)}}\mathbf{H}_{\mathcal{C}^{(t)}}^{\mathrm{H}} - \mathbf{h}_\ell\mathbf{h}_\ell^{\mathrm{H}}\right)^{-1}\right\}$;
$\qquad \text{s.t} \quad \ell \in \mathcal{C}^{(t)}$;
4: $\quad \mathcal{C}^{(t+1)} = \mathcal{C}^{(t)} - \{\ell\}$;
5: **end**
6: **Output**: $\mathcal{C}$ and $\mathbf{H}_{\mathcal{C}}$.

Algorithm 3 Allocating to the users SCAs

- The objective of Algorithm 3 is:

$$\left(\mathcal{U}_1,\ldots,\mathcal{U}_K\right) = \underset{\mathcal{U}_1,\ldots,\mathcal{U}_K}{\operatorname{argmin}} \sum_{k=1}^{K} \left[\left(\mathbf{H}_k\mathbf{H}_k^{\mathrm{H}}\right)^{-1}\right]_{k,k}$$

- Assign iteratively a selected antenna to a user

Require: $\mathbf{H}$, $\mathcal{C}$;

1: **Initialization**
2: $\quad \mathcal{N} = [N_{\mathrm{t}}] - \mathcal{C}$;
3: $\quad \mathcal{U}_k = \{\}, \qquad \forall k = 1,\ldots,K$;
4: $\quad \mathbf{H}_k = \mathbf{H}_{\mathcal{C}}, \qquad \forall k = 1,\ldots,K$;
5: **For** $k = 1 : K$
6: $\quad \widehat{\mathbf{H}}_{ki} = \left[\mathbf{h}_i, \mathbf{H}_k\right] \qquad \forall i \in \mathcal{N}$;
7: $\quad p_k = \left[\left(\mathbf{H}_k\mathbf{H}_k^{\mathrm{H}}\right)^{-1}\right]_{k,k}$;
8: $\quad p_{ki} = \left[\left(\widehat{\mathbf{H}}_{ki}\widehat{\mathbf{H}}_{ki}^{\mathrm{H}}\right)^{-1}\right]_{k,k}$;
9: $\quad \boldsymbol{\Delta}(k,i) = p_k - p_{ki}$;
10: **end**
11: **Repeat**
12: $\quad (k,\ell) = \underset{k,\ell\in\mathcal{N}}{\operatorname{argmax}} \ \boldsymbol{\Delta}(k,\ell)$

$\qquad\qquad$ s.t. $\ |\mathcal{U}_k| < N_{\mathrm{u}_k}$;

13: $\quad$ Allocate ℓth ant. to the kth user: $\mathcal{U}_k = \mathcal{U}_k \bigcup \{\ell\}$;
14: $\quad$ Remove ℓth ant. and set: $\mathcal{N} = \mathcal{N} - \{\ell\}$;
15: $\quad$ Update $\mathbf{H}_k = [\mathbf{H}_{\mathcal{U}_k}, \mathbf{H}_{\mathcal{C}}]$;
16: $\quad$ Update kth row of $\boldsymbol{\Delta}$ from steps 5 to 10;
17: **Until** $|\mathcal{N}| = 0$
18: **Output**: $\mathcal{U}_k, \qquad \forall k = 1,\ldots,K$;

Proposed DNN for the Dynamic PFC Architecture

- Using DNN to enable real-time antenna allocation
- DNN is used to predict the results of algorithms 2 and 3 directly
- **The dataset**: Generated with different channel realizations, and for each of these matrices, 99 noisy channel matrices
- **Input**: the matrix $\mathbf{X} \in \mathbb{R}^{K \times N_\mathrm{t} \times 3}$ containing the absolute value, real part, and imaginary part of the channel matrix.
- **The training label**: the binary matrix $\mathbf{Y}$ of the size $K \times N_\mathrm{t}$

For example: $\mathcal{U}_1 = \{1, 4, 8\}$ $\mathcal{U}_2 = \{2, 5, 7\}$ $\mathcal{C} = \{3, 6\}$

$$\mathbf{Y} = \begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \end{bmatrix}$$

Algorithm 4 Post-processing for the proposed DNN

- The trained DNN predicts the matrix $\widehat{\mathbf{Y}}$
- E.g. $\mathcal{U}_1 = \{1, 4, 8\}$ $\mathcal{U}_2 = \{2, 5, 7\}$ $\mathcal{C} = \{3, 6\}$

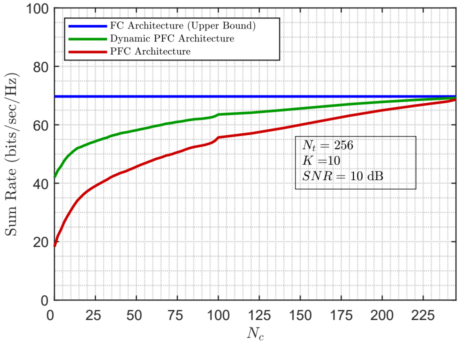
$$\widehat{\mathbf{Y}} = \begin{bmatrix} .9 & .2 & .8 & .7 & 0 & .9 & .7 & .9 \\ .1 & .9 & .9 & .2 & .9 & .9 & .8 & .2 \end{bmatrix}$$

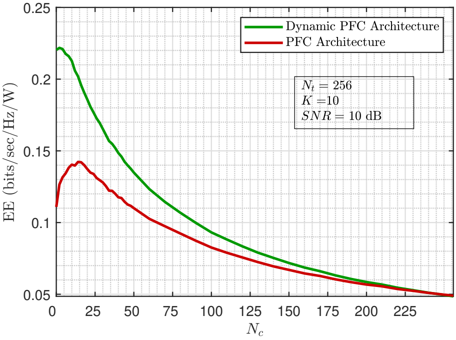
- Selecting the N_c columns of $\widehat{\mathbf{Y}}$ with the largest sum-value to set $\mathcal{C}$
- Assign the antennas to the users, a min-max approach
- Computation times (in milliseconds)

No. FACs, N_c	10	25	50	100	113
Alg. 2 & 3	1317	1219	1183	822	792
Proposed DNN	8.5	8.3	8.1	7.4	7.3

Require: $\widehat{\mathbf{Y}}$;
$\mathcal{N} = [N_t]$;
$\mathcal{U}_k = \{\}$, $\forall k = 1, \dots, K$;
$\mathcal{C} = \{\}$;
Repeat
  $\ell = \text{argmax}_{\ell \in \mathcal{N}} \sum_{k=1}^{K} \widehat{\mathbf{Y}}(k, \ell)$
  $\mathcal{C} = \mathcal{C} \cup \{\ell\}$;
  $\mathcal{N} = \mathcal{N} - \{\ell\}$;
Until $|\mathcal{C}| = N_c$
Repeat
  $\ell = \text{argmin}_{\ell \in \mathcal{N}} \sum_{k=1}^{K} \widehat{\mathbf{Y}}(k, \ell)$
  $k = \text{argmax}_k \; \widehat{\mathbf{Y}}(k, \ell)$ s.t. $|\mathcal{U}_k| < N_{u_k}$;
  $\mathcal{U}_k = \mathcal{U}_k \cup \{\ell\}$;
  $\mathcal{N} = \mathcal{N} - \{\ell\}$;
Until $|\mathcal{N}| = 0$
Outputs: $\mathcal{C}$, and $\mathcal{U}_k$, $\forall k = 1, \dots, K$.

Numerical results





Fully-Connected (FC)
Partially/Fully-Connected (PFC)

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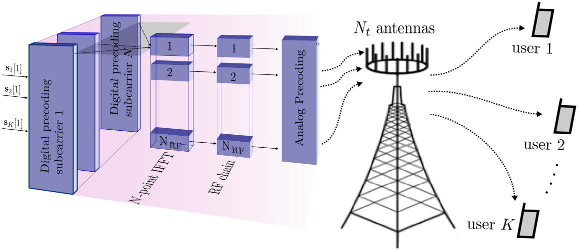
System Model



- A multiuser MISO-OFDM system that use FC strategy at analog network
- A shared analog beamformer needs to be designed to work for all subcarriers
- A digital beamformer is required for each subcarrier
- The received signal at the user's side

$$\mathbf{r}[n] = \mathbf{h}_k[n]\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[n]\mathbf{s}[n] + z[n],$$

- $\mathbf{F}_{\mathrm{RF}}$ is identical for all subcarriers

J. Beiranvand et al, "Hybrid beamforming with fixed phase shifters in ofdm-based multiuser miso systems," submitted to *IEEE Global Communications Conference (GLOBECOM)*, 2023

Problem Formulation

- The problem has a combinatorial nature due to the limited points in the feasible set.

$$
\begin{aligned}
\underset{\mathbf{F}_{\mathrm{RF}},\{\mathbf{F}_{\mathrm{BB}}[n]\}_{n=1}^{N}}{\text{maximize}} \quad & \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K}\log(1+\mathrm{SINR}_{k,n}) \\
\text{s.t} \quad & \mathrm{Tr}\left\{\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[n]\mathbf{F}_{\mathrm{BB}}^{\mathrm{H}}[n]\mathbf{F}_{\mathrm{RF}}^{\mathrm{H}}\right\} \leq P, \forall n, \\
& \mathbf{F}_{\mathrm{RF}}(i,j) \in \mathcal{F}_{N_{\mathrm{ps}}},
\end{aligned}
$$

- Assume that the feasible set encompasses all points inside a circle with a radius of r_0.

$$
\begin{aligned}
\underset{\mathbf{F},\{\mathbf{F}_{\mathrm{BB}}[n]\}_{n=1}^{N}}{\text{maximize}} \quad & \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K}\log(1+\mathrm{SINR}_{k,n}) \\
\text{s.t} \quad & \mathrm{Tr}\left\{\mathbf{F}\mathbf{F}_{\mathrm{BB}}[n]\mathbf{F}_{\mathrm{BB}}^{\mathrm{H}}[n]\mathbf{F}^{\mathrm{H}}\right\} \leq P, \forall n, \\
& |\mathbf{F}(i,j)| \leq r_0.
\end{aligned}
$$

- The new constraint on $\mathbf{F}$ can be temporarily removed, because the digital beamforming part can satisfy the transmit power constraint.
- We employ the Lagrangian dual transformation technique using FP method.

Step 1 - Lagrangian Dual Transformation

- Moving the SINR term outside the logarithm by applying *Lagrangian Dual Transformation* [71]
- The objective function can be expressed as:

$$\begin{aligned}\mathcal{G}_r\left(\mathbf{F}, \mathbf{F}_{\mathrm{BB}}[n], \boldsymbol{\gamma}[n]\right) = &\sum_{k=1}^{K} \log_2\left(1+\gamma_k[n]\right) - \sum_{k=1}^{K} \gamma_k[n] \\ &+ \sum_{k=1}^{K}\left(1+\gamma_k[n]\right)\left(\mathbf{h}_k[n]\mathbf{F}\mathbf{f}_{\mathrm{BB}_k}[n]\right)^{\mathrm{H}} \\ &\times\left(\sigma_z^2 + \sum_{j=1}^{K} \mathbf{h}_k[n]\mathbf{F}\mathbf{f}_{\mathrm{BB}_j}[n]\mathbf{f}_{\mathrm{BB}_j}^{\mathrm{H}}[n]\mathbf{F}^{\mathrm{H}}\mathbf{h}_k[n]^{\mathrm{H}}\right)^{-1} \mathbf{h}_k[n]\mathbf{F}\mathbf{f}_{\mathrm{BB}_k}[n],\end{aligned}$$

- Red term is the ratio term
- The optimal $\gamma_k[n]$ can be obtained by setting $\frac{\partial \mathcal{G}_r}{\partial \gamma_k[n]} = 0$:

$$\gamma_k^{\star}[n] = \mathbf{f}_{\mathrm{BB}_k}^{\mathrm{H}}[n]\mathbf{F}^{\mathrm{H}}\mathbf{h}_k^{\mathrm{H}}[n]\left(\sigma_z^2 + \sum_{j\neq k}^{K} \mathbf{h}_k[n]\mathbf{F}\mathbf{f}_{\mathrm{BB}_j}[n]\mathbf{f}_{\mathrm{BB}_j}^{\mathrm{H}}[n]\mathbf{F}^{\mathrm{H}}\mathbf{h}_k^{\mathrm{H}}[n]\right)^{-1} \mathbf{h}_k[n]\mathbf{F}\mathbf{f}_{\mathrm{BB}_k}[n].$$

Step 2 - Quadratic Transformation

- Decoupling the numerator and denominator of each ratio term by applying Quadratic Transformation [71]
- Expressing the objective function $\mathcal{G}_r$ into a new form $\mathcal{G}_q$ as follows:

$$\begin{aligned}\mathcal{G}_q\left(\mathbf{F}, \mathbf{F}_{\mathrm{BB}}[n], \mathbf{Y}[n], \boldsymbol{\gamma}[n]\right) = &\sum_{k=1}^{K} \log_2\left(1+\gamma_k[n]\right) \\ &- \sum_{k=1}^{K} \gamma_k[n] + \sum_{k=1}^{K} 2\sqrt{1+\gamma_k[n]}\,\mathfrak{Re}\left(y_k[n]^{\mathrm{H}}\mathbf{h}_k[n]\mathbf{F}\mathbf{f}_{\mathrm{BB}_k}[n]\right) \\ &- y_k[n]^{\mathrm{H}}\left(\sigma_z^2 + \sum_{j=1}^{K}\mathbf{h}_k[n]\mathbf{F}\mathbf{f}_{\mathrm{BB}_j}[n]\mathbf{f}_{\mathrm{BB}_j}^{\mathrm{H}}[n]\mathbf{F}^{\mathrm{H}}\mathbf{h}_k^{\mathrm{H}}[n]\right) y_k[n],\end{aligned}$$

- With the other variables fixed, the optimal $y_k[n]$ can be obtained by solving $\frac{\partial \mathcal{G}_q}{\partial y_k[n]} = 0$:

$$y_k^{\star}[n] = \left(\sigma_z^2 + \sum_{j=1}^{K}\mathbf{h}_k[n]\mathbf{F}\mathbf{f}_{\mathrm{BB}_j}[n]\mathbf{f}_{\mathrm{BB}_j}^{\mathrm{H}}[n]\mathbf{F}^{\mathrm{H}}\mathbf{h}_k^{\mathrm{H}}[n]\right)^{-1}\sqrt{1+\gamma_k[n]}\mathbf{h}_k[n]\mathbf{F}\mathbf{f}_{\mathrm{BB}_k}[n].$$

- Likewise, the optimal $\mathbf{f}_{\mathrm{BB}_k}[n]$ is

$$\mathbf{f}_{\mathrm{BB}_k}^{\star}[n] = \left(\eta\mathbf{F}^{\mathrm{H}}\mathbf{F} + \sum_{j=1}^{K}\mathbf{F}^{\mathrm{H}}\mathbf{h}_k^{\mathrm{H}}[n]y_j[n]y_j^{\mathrm{H}}[n]\mathbf{h}_k[n]\right)^{-1}\sqrt{1+\gamma_k[n]}\mathbf{F}^{\mathrm{H}}\mathbf{h}_k^{\mathrm{H}}[n]y_k,$$

Step 3 - Solving Optimization Problem

- With the other variables fixed, the optimization problem of $\mathbf{F}$ can be formulated as follows:

$$\begin{aligned} \underset{\mathbf{F}}{\text{maximize}} \quad & \delta(\mathbf{F}) \\ \text{s.t} \quad & \mathrm{Tr}\left\{ \left| \mathbf{F}\mathbf{F}_{\mathrm{BB}}[n] \right|^2 \right\} \leq P, \forall n, \end{aligned}$$

where

$$\delta(\mathbf{F}) = \sum_{n=1}^{N} \sum_{k=1}^{K} \sqrt{1+\gamma_k[n]} 2\mathfrak{Re}\left(y_k[n]^{\mathrm{H}} \mathbf{h}_k[n] \mathbf{F} \mathbf{f}_{\mathrm{BB}_k}[n] \right) - \left| y_k[n] \right|^2 \sum_{j=1}^{K} \left| \mathbf{h}_k[n] \mathbf{F} \mathbf{f}_{\mathrm{BB}_j}[n] \right|^2 .$$

- The problem is a convex problem, which can be solved by a convex optimization solver such as CVX-MoseK.

Algorithm 5 Hybrid beamforming for wideband channels

- The three steps can be iteratively executed as summarized in Algorithm 5

Require: K users, N subcarriers, N_t, N_RF RF chains;
1: **Initialization:** $\mathbf{F}$, $\mathbf{F}_\mathrm{BB}[n]$ for all n;
Ensure: Max sum rate;
2: **repeat**
3: Update $\gamma[n]$ for all n;
4: Update $\mathbf{y}[n]$ for all n;
5: Update $\mathbf{F}$;
6: Update $\mathbf{F}_\mathrm{BB}[n]$ for all n;
7: **until** Convergence
8: Obtain $\mathbf{F}_\mathrm{RF}$ via mapping $\mathbf{F}$ into $\mathcal{F}_{N_\mathrm{ps}}$.

- Algorithm 5 can handle the constraints directly, but the number of constraints can become very large
- High computational complexity makes practical implementation difficult

Algorithm 6 Low-complex precoder design for wideband channels

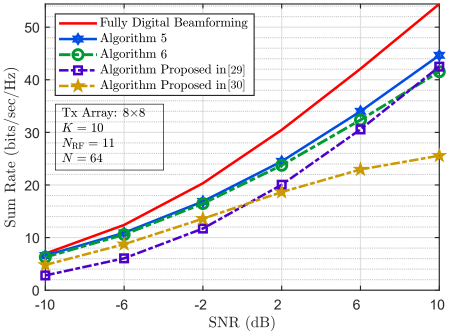
- Designing $\mathbf{F}_{\mathrm{RF}}$ to include the principal components of the fully digital precoder matrices

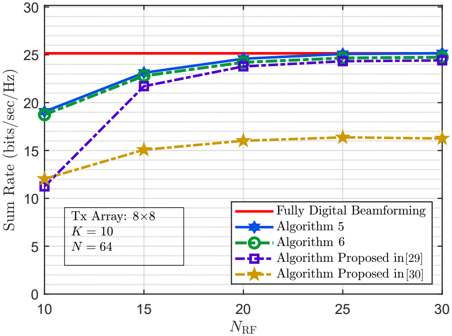
$$\widetilde{\mathbf{F}}_{\mathrm{opt}} = \left[\mathbf{F}_{\mathrm{opt}_1}, \mathbf{F}_{\mathrm{opt}_2}, \ldots, \mathbf{F}_{\mathrm{opt}_N}\right],$$

- Computing SVD of $\widetilde{\mathbf{F}}_{\mathrm{opt}}$ as $\widetilde{\mathbf{F}}_{\mathrm{opt}} = \mathbf{U}\mathbf{S}\mathbf{V}^{\mathrm{H}}$,
- Selecting the first N_{RF} columns of $\mathbf{U}$, denoted as $\mathbf{U}_{N_{\mathrm{RF}}}$
- Obtaining $\mathbf{F}_{\mathrm{RF}}$ via mapping $\mathbf{U}_{N_{\mathrm{RF}}}$ into $\mathcal{F}_{N_{\mathrm{ps}}}$

Require: K users, N subcarriers, N_{t}, N_{RF} RF chains;
Initialization:
    Obtain $\mathbf{U}_{N_{\mathrm{RF}}}$ via calculating SVD of $\widetilde{\mathbf{F}}_{\mathrm{opt}}$;
    Obtain $\mathbf{F}_{\mathrm{RF}}$ via mapping $\mathbf{U}_{N_{\mathrm{RF}}}$ into $\mathcal{F}_{N_{\mathrm{ps}}}$;
Ensure: Max sum rate;
repeat
    Update $\gamma[n]$ for all n;
    Update $\mathbf{y}[n]$ for all n;
    Update $\mathbf{F}_{\mathrm{BB}}[n]$ for all n;
until Convergence

Numerical results





Conclusion

- Addressing the computational complexity issue by proposing an algorithm to obtain beamforming matrices
- Addressing the hardware complexity issue associated with the analog network
    - Hardware implementation: analyze the number of PSs
    - Mapping strategy: proposing PFC mapping strategy
- Proposing a novel approach for designing hybrid precoding for wideband channels

Perspectives

- Devolve an approach to estimate the channel for the proposed systems.
- Explore the application of the PFC mapping strategy to the SPS and QPS hardware implementations.
- Investigate the extension of the PFC mapping strategy to multicarrier scenarios
- User scheduling and user clustering

Publications

- **J. Beiranvand** et al, "An Efficient Low-Complexity Method to Calculate Hybrid Beamforming Matrices for mmWave Massive MIMO Systems," in *IEEE Open Journal of the Communications Society*, vol. 2, pp. 1239-1248, 2021, doi: 10.1109/OJCOMS.2021.3084343.
- **J. Beiranvand** et al, "How Many Fixed Phase Shifters Are Needed in a Hybrid BF Structure?," *ICC 2022 - IEEE International Conference on Communications*, Seoul, Korea, Republic of, 2022, pp. 444-449, doi: 10.1109/ICC45855.2022.9838503.
- **J. Beiranvand** et al, "An Efficient Beamforming Architecture to Handle the Trade-Off Between Performance and Hardware Complexity in Multiuser Massive MISO Systems," in *IEEE Access*, vol. 10, pp. 132853-132862, 2022, doi: 10.1109/ACCESS.2022.3230326.
- **J. Beiranvand** et al, “Hybrid beamforming with fixed phase shifters in ofdm-based multiuser miso systems,” submitted to *IEEE Global Communications Conference (GLOBECOM)*, 2023

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Thanks for your attention