Main Presentation

Hybrid Codebook Construction and Sum Rate Maximization in mmWave Multiuser Systems

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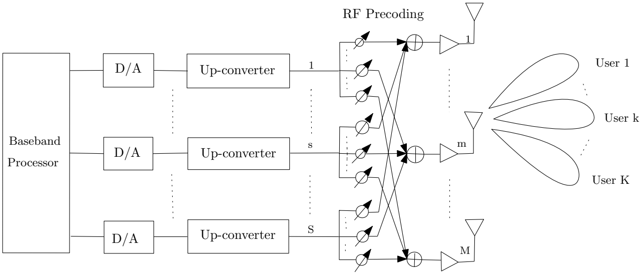
- To reduce the losses we use beamforming techniques to generate beamforming vectors
- We have simulated a hybrid precoding method from the literature to generate the RF precoder and baseband precoder to select the beamformers[1]

Consider a multiple input single output (MISO) system,



The system is consists of a baseband processor, digital-to-analog converter (DAC), upconverter, S RF chains, M transmit antennas, and K number of users.

Notations

The system model is expressed as

$$\mathbf{y} = \mathbf{H}\underline{\mathbf{F}}\underline{\mathbf{G}}\mathbf{s} + \mathbf{n}$$

Here,
$\mathbf{H}$: channel matrix of the system of size $K \times M$,
$\underline{\mathbf{F}}$: RF precoder of size $M \times S$,
$\underline{\mathbf{G}}$: baseband precoder of size $S \times K$,
$\mathbf{s}$: transmitted vector of size $K \times 1$,
$\mathbf{n}$: noise vector of size $K \times 1$,
$\mathbf{y}$: received vector of size $K \times 1$.

Here, $M \geq S \geq K$

Channel Model

Here, $\mathbf{s}^T = [s_1, \ldots, s_K]$ with $s_k \sim \mathcal{CN}(0,1)$, $\forall\, k \in \mathcal{K} \triangleq \{1, 2, \ldots, K\}$

$\mathbf{H}^H = [\mathbf{h}_1, \ldots, \mathbf{h}_K]$. Here, $\mathbf{h}_k$ is given by

$$\mathbf{h}_k = \sqrt{\frac{M}{N_{cl} N_{ray}}} \sum_{m_p=1}^{N_{cl}} \sum_{n_p=1}^{N_{ray}} \alpha_{m_p,n_p} \mathbf{a}\left(\phi_{m_p,n_p}\right)$$

$$\text{where, } \mathbf{a}_{ULA}(\phi) = \sqrt{\frac{1}{M}} \left[1, e^{j\frac{2\pi}{\lambda} d\, sin(\phi)}, \ldots, e^{j(M-1)\frac{2\pi}{\lambda} d\, sin(\phi)}\right]$$

λ is the signal wavelength
d is the antenna spacing
ϕ is the angle of departure (AoD)

$\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I_K})$ is the AWGN noise vector.
$\alpha_{m_p,n_p} \sim \mathcal{CN}(0, \sigma^2_{m_p})$

Sum Rate Expression

Problem of maximizing system sum rate is given as

$$\max_{\underline{F},\underline{G}} \sum_{k=1}^{K} \underline{R}_k$$

$$\text{s.t.} \quad \underline{R}_k = \log\left(1 + \underline{\text{SINR}}_k\right) \geq \gamma_k, \; \forall k \in \mathcal{K}$$

$$\underline{\mathbf{F}} \in \mathcal{F}_{RF}, \; \|\underline{\mathbf{FG}}\|_{\mathcal{F}}^2 \leq P$$

$$\underline{\text{SINR}}_k = \frac{|\mathbf{h_k^H}\underline{\mathbf{F}}\underline{\mathbf{g_k}}|^2}{\sum_{l=1,l\neq k}^{K} |\mathbf{h}_k^H \underline{\mathbf{F}}\underline{\mathbf{g}_l}|^2 + \sigma^2}$$

RF Codebook Design

Some examples of the RF codebooks are

- q-bit quantizer Codebook

$$\mathbf{F}(m,n) = \frac{1}{\sqrt{M}} e^{j\frac{\pi(4(m-1)(n-1)-2N)}{2^{q+1}}}, \ \forall m \in \mathcal{M}, \forall n \in \mathcal{N}$$

- IEEE 802.15.3c Codebook

$$\mathbf{F}(m,n) = \frac{1}{\sqrt{M}} e^{j\frac{\pi}{2}\text{floor}\left(\frac{4(m-1)\left(\text{mod}\left((n-1)+\frac{N}{4},N\right)\right)}{N}\right)}, \ \forall m \in \mathcal{M}, \forall n \in \mathcal{N}$$

- DFT Codebook

$$\mathbf{F}(m,n) = \frac{1}{\sqrt{M}} e^{-\frac{j2\pi(m-1)(n-1)}{M}}, \ \forall m \in \mathcal{M}, \forall n \in \mathcal{N}$$

Here, $\mathcal{M} \in \{1,\ldots,M\}$, $\mathcal{N} \in \{1,\ldots,N\}$

Contd.

- DFT-based Multilevel Codebook [2]

$$\mathcal{F}_m = \left\{ f_1^{(m)}, f_2^{(m)}, \ldots, f_{M/N}^{(m)} \right\}$$
$$= \left\{ \frac{1}{\sqrt{N}} \sum_{p=1}^{N} \mathbf{u}_t(p) e^{j\omega_m p}, \frac{1}{\sqrt{N}} \sum_{p=N+1}^{2N} \mathbf{u}_t(p) e^{j\omega_m p}, \ldots, \right.$$
$$\left. \frac{1}{\sqrt{N}} \sum_{p=M-N+1}^{M} \mathbf{u}_t(p) e^{j\omega_m p} \right\}$$

$$\mathbf{u}_t(n) = \frac{1}{\sqrt{M}} \left[1, e^{-j\frac{2\pi}{M}\omega_m\left(n-\frac{M+1}{2}\right)}, e^{-j\frac{2\pi}{M}\omega_m 2\left(n-\frac{M+1}{2}\right)}, \ldots, e^{-j\frac{2\pi}{M}\omega_m (M-1)\left(n-\frac{M+1}{2}\right)} \right.$$

$\omega_m \in \left[-\frac{\pi}{M}, \pi\left(1-\frac{1}{M}\right)\right]$ and is selected by minimizing $var\left(\left|\mathbf{u}_t^H(n)\mathbf{f}_k^{(m)}\right|\right)$.

Beam Sweep Procedure

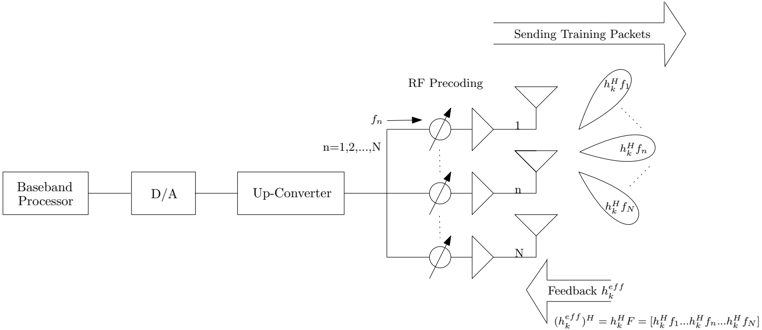


Figure: Beam-sweep Procedure

Virtual Communication System for CSIT

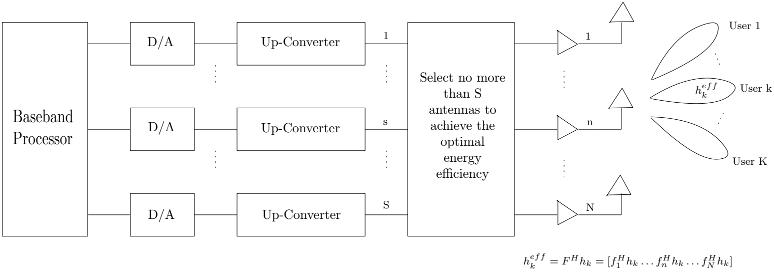


Figure: Virtual Multiuser Communication System

Baseband Precoder Design

Sum rate maximization problem is expressed as

$$\max_{\mathbf{G}} \sum_{k=1}^{K} R_k,$$

$$\text{s.t. } R_k = \log\left(1 + \text{SINR}_k\right),$$

$$\sum_{k=1}^{K} \|\mathbf{F}\mathbf{g}_k\|_2^2 \leq P, \; \|\ddot{\mathbf{g}}\|_0 \leq S,$$

where, $\ddot{\mathbf{g}} = \left[\|\tilde{\mathbf{g}}_1\|_2, \ldots, \|\tilde{\mathbf{g}}_N\|_2\right]^T$

$$\text{SINR}_k = \frac{|\mathbf{h}_k^H \mathbf{F}\mathbf{g}_k|^2}{\sum_{l=1, l\neq k}^{K} |\mathbf{h}_k^H \mathbf{F}\mathbf{g}_l|^2 + \sigma^2}$$

Contd.

We will introduce some variables $a_k, b_k, \forall k \in \mathcal{K}$, So, the sum rate maximization problem can be rewritten as

$$\min_{\{\mathbf{g}_k, a_k, b_k\}} -\sum_{k=1}^{K} b_k,$$
$$\text{s.t. } 1 + a_k \geq e^{b_k}, \forall k \in \mathcal{K},$$
$$\text{SINR}_k \geq a_k, \text{SINR}_k \geq \bar{\gamma}_k, \forall k \in \mathcal{K},$$
$$\sum_{k=1}^{K} \|\mathbf{F}\mathbf{g}_k\|_2^2 \leq P, \|\ddot{\mathbf{g}}\|_0 \leq S,$$

where $\bar{\gamma}_k = e^{\gamma_k} - 1$

Rearranging the problem

To overcome noncovex difficulties

$$\min_{\{\mathbf{g}_k, a_k, b_k\}} -\sum_{k=1}^{K} b_k + \lambda \|\ddot{\mathbf{g}}\|_0,$$

$$\text{s.t. } 1 + a_k \geq e^{b_k}, \forall k \in \mathcal{K}, \sum_{k=1}^{K} \|\mathbf{F}\mathbf{g}_k\|_2^2 \leq P,$$

$$\text{SINR}_k \geq a_k, \text{ SINR}_k \geq \bar{\gamma}_k, \forall k \in \mathcal{K},$$

Here, λ control the sparsity of solution, i.e., the larger λ the solution is more sparse.

Approximate Problem

Problem can be further approximated as

$$\min_{\{\mathbf{g}_k, a_k, b_k\}} -\sum_{k=1}^{K} b_k + \lambda \|\mathbf{G}\|_{1,\infty}^2,$$

$$\text{s.t. } 1 + a_k \geq e^{b_k}, \forall k \in \mathcal{K}, \sum_{k=1}^{K} \|\mathbf{F}\mathbf{g}_k\|_2^2 \leq P,$$

$$\text{SINR}_k \geq a_k, \text{SINR}_k \geq \bar{\gamma}_k, \forall k \in \mathcal{K},$$

where $\|\mathbf{G}\|_{1,\infty} = \sum_{n=1}^{N} \max_k |\mathbf{g}_k(n)|$ is the $l_{1,\infty}$-norm of matrix $\mathbf{G}$.

Contd.

Here, $\|\mathbf{G}\|_{1,\infty}^2$ can be rewritten as

$$\begin{aligned}\|\mathbf{G}\|_{1,\infty}^2 &= \left(\sum_{n=1}^{N} \max_k |\mathbf{g}_k(n)|\right)^2, \\ &= \sum_{n=1}^{N}\sum_{m=1}^{N}\left(\left(\max_k |\mathbf{g}_k(n)|\right)\left(\max_k |\mathbf{g}_k(m)|\right)\right), \\ &= \sum_{n=1}^{N}\sum_{m=1}^{N} \max_{i,j\in\{1,\dots,K\}} |\mathbf{X}_{i,j}(n,m)|,\end{aligned}$$

where $\mathbf{X}_{i,j} = \mathbf{g}_i\mathbf{g}_j^H$, $\forall i,j$. So, $\mathbf{X}_{i,i} = \mathbf{g}_i\mathbf{g}_i^H$, therefore $\mathbf{X}_{i,i} \succeq 0$ and $\text{rank}(\mathbf{X}_{i,i}) = 1$, $\forall i$.

Approximate Problem

Problem can be further approximated as

$$\min_{\{\mathbf{X}_{i,j}, a_k, b_k\}} -\sum_{k=1}^{K} b_k + \lambda \|\mathbf{G}\|_{1,\infty}^2,$$

$$\text{s.t. } 1 + a_k \geq e^{b_k}, \forall k \in \mathcal{K}, \sum_{k=1}^{K} \text{tr}\left(\tilde{\mathbf{F}}\mathbf{X}_{k,k}\right) \leq P,$$

$$\text{SINR}_k \geq a_k, \text{SINR}_k \geq \bar{\gamma}_k, \forall k \in \mathcal{K}, \mathbf{X}_{k,k} \succeq \mathbf{0}, \forall k \in \mathcal{K},$$

$$\text{rank}\left(\mathbf{X}_{i,j}\right) = 1, \forall i, j,$$

where $\tilde{\mathbf{F}} = \mathbf{F}^H \mathbf{F}$, and

$$\text{SINR}_k = \frac{\text{tr}\left(\mathbf{H}_k \mathbf{X}_{k,k}\right)}{\sum_{l=1, l \neq k}^{K} \text{tr}\left(\mathbf{H}_k \mathbf{X}_{l,l}\right) + \sigma^2}$$

where $\mathbf{H}_k = \mathbf{F}^H \mathbf{h}_k \mathbf{h}_k^H \mathbf{F}, \forall k \in \mathcal{K}$.

Further Approximation

Let $\mathbf{X}_k = \mathbf{X}_{k,k}$, $\forall k \in \mathcal{K}$ and $\mathbf{Z}(n,m) = \max_{k \in \mathcal{K}} |\mathbf{X}_k(n,m)|$, $\forall k \in \mathcal{K}$.

We will drop the nonconvex constraints $\text{rank}(\mathbf{X}_k) = 1$.

$$\min_{\{\mathbf{X}_k, a_k, b_k\}, \mathbf{Z}} -\sum_{k=1}^{K} b_k + \lambda \text{tr}\left(\mathbf{1}_{N \times N} \mathbf{Z}\right)$$

$$\text{s.t. } 1 + a_k \geq e^{b_k},\ \forall k \in \mathcal{K},\ \sum_{k=1}^{K} \text{tr}\left(\tilde{\mathbf{F}} \mathbf{X}_k\right) \leq P,$$

$$\text{SINR}_k \geq a_k,\ \text{SINR}_k \geq \bar{\gamma}_k,\ \forall k \in \mathcal{K},$$

$$\mathbf{X}_k \succeq \mathbf{0},\ \mathbf{Z} \geq |\mathbf{X}_k|,\ \forall k \in \mathcal{K},$$

Contd.

We will introduce some new variables $\psi_k.\phi_k$, $\forall k \in \mathcal{K}$. The problem can be rewritten as

$$\min_{\{\mathbf{X}_k, a_k, b_k, \psi_k, \phi_k\}, \mathbf{Z}} -\sum_{k=1}^{K} b_k + \lambda \mathrm{tr}\left(\mathbf{1}_{N\times N}\mathbf{Z}\right),$$

$$\text{s.t. } \psi_k^2 \leq \mathrm{tr}\left(\mathbf{H}_k\mathbf{X}_k\right), \ \mathbf{X}_k \succeq \mathbf{0}, 1 + a_k \geq e^{b_k}, \forall k \in \mathcal{K}$$

$$\sum_{l=1, l\neq k}^{K} \mathrm{tr}\left(\mathbf{H}_k\mathbf{X}_{l,l}\right) + \sigma^2 \leq \phi_k, \forall k \in \mathcal{K}, \sum_{k=1}^{K} \mathrm{tr}\left(\tilde{\mathbf{F}}\mathbf{X}_k\right) \leq P,$$

$$\sum_{l=1, l\neq k}^{K} \bar{\gamma}_k \mathrm{tr}\left(\mathbf{H}_k\mathbf{X}_{l,l}\right) + \bar{\gamma}_k\sigma^2 \leq \mathrm{tr}\left(\mathbf{H}_k\mathbf{X}_k\right), \ \frac{\psi_k^2}{\phi_k} \geq a_k, \forall K \in \mathcal{K},$$

$$\begin{bmatrix} \mathbf{Z}(n,m) - \Re(\mathbf{X}_k(n,m) & \Im(\mathbf{X}_k(n,m)) \\ \Im(\mathbf{X}_k(n,m)) & \mathbf{Z}(n,m) + \Re(\mathbf{X}_k(n,m) \end{bmatrix} \succeq \mathbf{0}, \forall k \in \mathcal{K}, m, n.$$

Final Convex Problem

The constraint $\frac{\psi_k^2}{\phi_k} \geq a_k$ is still nonconvex. So, the constraint can be approximated as

$$\frac{\psi_k^2}{\phi_k} \geq \Phi_k^{(l)}(\psi_k, \phi_k) \triangleq 2\frac{\psi_k^{(l)}}{\phi_k^{(l)}}\psi_k - \left(\frac{\psi_k^{(l)}}{\phi_k^{(l)}}\right)^2 \phi_k, \forall k \in \mathcal{K},$$

Now, we will solve the series of convex optimization problem. Here, l denotes the lth iteration. $(\psi_k^{(l)}, \phi_k^{(l)}) \leftarrow (\psi_k, \phi_k)$ at the lth iteration. $\Phi_k^{(l)}(\psi_k, \phi_k)$ is determined at the lth iteration.

Contd.

So, the approximate value of convex problem at the $(l+1)$th iteration can be

$$\min_{\{\mathbf{X}_k, a_k, b_k, \psi_k, \phi_k\}\mathbf{Z}} -\sum_{k=1}^{K} b_k + \lambda \text{tr}(\mathbf{1}_{N\times N}\mathbf{Z}),$$

$$\text{s.t. } \psi_k^2 \leq \text{tr}\left(\mathbf{H}_k\mathbf{X}_k\right), \mathbf{X}_k \succeq \mathbf{0}, 1 + a_k \geq e^{b_k}, \forall k \in \mathcal{K},$$

$$\sum_{l=1, l\neq k}^{K} \text{tr}\left(\mathbf{H}_k\mathbf{X}_l\right) + \sigma^2 \leq \phi_k, \forall k \in \mathcal{K}, \sum_{k=1}^{K} \text{tr}\left(\tilde{\mathbf{F}}\mathbf{X}_k\right) \leq P,$$

$$\sum_{l=1, l\neq k}^{K} \bar{\gamma}_k \text{tr}\left(\mathbf{H}_k\mathbf{X}_l\right) + \bar{\gamma}_k\sigma^2 \leq \text{tr}\left(\mathbf{H}_k\mathbf{X}_k\right),$$

$$\Phi_k^{(l)}(\psi_k, \phi_k) \geq a_k, \forall k \in \mathcal{K},$$

$$\begin{bmatrix} \mathbf{Z}(n,m) - \Re(\mathbf{X}_k(n,m) & \Im(\mathbf{X}_k(n,m)) \\ \Im(\mathbf{X}_k(n,m)) & \mathbf{Z}(n,m) + \Re(\mathbf{X}_k(n,m) \end{bmatrix} \succeq \mathbf{0}, \forall k \in \mathcal{K}, m, n.$$

Solution of the Convex Problem

Algorithm for optimal solution

Fix a value of λ. Let the value of our objective function is τ and $\tau^{(l)}$is the value of τ at the lth iteration.

1: Let $l = 0$, take some initial points as $\Gamma^{(l)}$ and get $\tau^{(l)}$.
2: Solve the convex problem with $\Gamma^{(l)}$, and obtain new values of the Γ and τ.
3: If $|\tau - \tau^{(l)}| \leq \zeta$, then τ, Γ will be our optimal solution, otherwise $\Gamma^{(l)} \leftarrow \Gamma, \tau^{(l)} \leftarrow \tau$ and go to step 2.

Selection of λ

Let L^λ be the number of nonzero diagonal entries in $\mathbf{Z}$.

Algorithm for choosing λ

1: Generate initial points λ_L, λ_U and compute $\tilde{\tau}^T = \sum_{k=1}^{K} b_k$ and denote Ξ^T as the temoprary solution of the convex problem. Let *flag* $= 1$

2: **while** flag **do**

3: Let $\lambda = \frac{\lambda_L + \lambda_U}{2}$.

4: Solve the convex problem with λ, then obtain the solution of it after iteration and $\tilde{\tau}^\lambda$

5: If $L^\lambda > S$, let $\lambda_L = \lambda$, otherwise, let $\lambda_U = \lambda$.

6: If $|\tilde{\tau}^\lambda - \tilde{\tau}^T| \leq \zeta$ and $L^\lambda \leq S$, then let *flag*$=0$ and output the solution of convex problem. Otherwise, $\Xi^T \leftarrow \Xi^\lambda, \tilde{\tau}^T \leftarrow \tilde{\tau}^\lambda$

7: **end while**

Refining Solution

$\hat{\mathbf{F}}$ is obtained by choosing L^{λ} codewords from RF codebook.
$\bar{\mathbf{h}}_k = \hat{\mathbf{F}}^H \mathbf{h}_k$ is our effective channel.

Now we will refine our solution

$$\max_{\{\bar{g_k}\}} \sum_{k=1}^{K} \bar{R}_k,$$
$$\text{s.t. } \overline{\text{SINR}}_k \geq \bar{\gamma}_k, \forall k \in \mathcal{K},$$
$$\sum_{k=1}^{K} \|\hat{F}\bar{g}_k\|_2^2 \leq P,$$

where $\bar{R}_k = \log\left(1 + \overline{\text{SINR}}_k\right)$, and $\overline{\text{SINR}}_k$ is given by

$$\overline{\text{SINR}}_k \triangleq \frac{\|\bar{\mathbf{h}}_k^H \bar{\mathbf{g}}_k\|_2^2}{\sum_{l=1, l\neq K}^{K} \|\bar{\mathbf{h}}_k^H \bar{\mathbf{g}}_l\|_2^2 + \sigma^2}.$$

Rearranging the Problem

We introduce variable $\bar{a}_k, \bar{b}_k, \bar{\phi}_k$, the problem can be reformulated as

$$\max_{\{\bar{\mathbf{g}}_k, \bar{a}_k, \bar{b}_k, \bar{\phi}_k\}} \sum_{k=1}^{K} \bar{b}_k,$$

$$\text{s.t. } 1 + \bar{a}_k \geq e^{\bar{b}_k}, \forall k \in \mathcal{K}, \sum_{k=1}^{K} \|\hat{F}\bar{g}_k\|_2^2 \leq P$$

$$\frac{\|\bar{\mathbf{h}}_k^H \bar{\mathbf{g}}_k\|_2^2}{\bar{\phi}_k} \geq \bar{\gamma}_k, \forall \frac{\|\bar{\mathbf{h}}_k^H \bar{\mathbf{g}}_k\|_2^2}{\bar{\phi}_k} \geq \bar{a}_k, \forall k \in \mathcal{K},$$

$$\sum_{l=1, l \neq K}^{K} \|\bar{\mathbf{h}}_k^H \bar{\mathbf{g}}_l\|_2^2 + \sigma^2 \leq \bar{\phi}_k, \forall k \in \mathcal{K},$$

Final Sum Rate Maximization Problem

As the problem is nonconvex, we can approximate the constraint by

$$\frac{\|\bar{h}_k^H \bar{g}_k\|_2^2}{\bar{\phi}_k} \geq \bar{\Phi}_k^{(l)}\left(\bar{g}_k \bar{\phi}_k\right) \triangleq \frac{2\Re\left(\left(\bar{g}_k^{(l)}\right)^H \bar{h}_k \bar{h}_k^H \bar{g}_k\right)}{\bar{\phi}_k^{(l)}} - \left(\frac{\|\bar{h}_k^H \bar{g}_k^{(l)}\|_2}{\bar{\phi}_k^{(l)}}\right)^2 \bar{\phi}_k,$$
$$\forall k \in \mathcal{K},$$

Here l denotes the lth iteration. We can write

$$\bar{\Phi}_k^{(l)}\left(\bar{g}_k, \bar{\phi}_k\right) \geq \bar{\gamma}_k,\ \bar{\Phi}_k^{(l)}\left(\bar{g}_k, \bar{\phi}_k\right) \geq \bar{a}_k,\ \forall k \in \mathcal{K}.$$

Contd.

We solve the following convex problem to obtain the optimal solution

$$\max_{\{\bar{\mathbf{g}}_k, \bar{a}_k, \bar{b}_k, \bar{\phi}_k\}} \sum_{k=1}^{K} \bar{b}_k,$$

$$\text{s.t. } 1 + \bar{a}_k \geq e^{\bar{b}_k}, \forall k \in \mathcal{K}, \sum_{k=1}^{K} \|\hat{F}\bar{g}_k\|_2^2 \leq P$$

$$\sum_{l=1, l \neq K}^{K} \|\bar{\mathbf{h}}_k^H \bar{\mathbf{g}}_l\|_2^2 + \sigma^2 \leq \bar{\phi}_k, \forall k \in \mathcal{K},$$

$$\bar{\Phi}_k^{(l)} \left(\bar{g}_k, \bar{\phi}_k\right) \geq \bar{\gamma}_k, \; \bar{\Phi}_k^{(l)} \left(\bar{g}_k, \bar{\phi}_k\right) \geq \bar{a}_k, \; \forall k \in \mathcal{K}.$$

Algorithm for optimal solution

Let the value of our objective function is $\bar{\tau}$ and $\bar{\tau}^{(l)}$is the value of $\bar{\tau}$ at the lth iteration.

1: Let $l = 0$, take some initial points as $\bar{\Gamma}^{(l)}$ and get $\bar{\tau}^{(l)}$.
2: Solve the convex problem with $\bar{\Gamma}^{(l)}$, and obtain new values of the $\bar{\Gamma}$ and $\bar{\tau}$.
3: If $|\bar{\tau} - \bar{\tau}^{(l)}| \leq \zeta$, then $\bar{\tau}, \bar{\Gamma}$ will be our optimal solution, otherwise $\bar{\Gamma}^{(l)} \leftarrow \bar{\Gamma}, \bar{\tau}^{(l)} \leftarrow \bar{\tau}$ and go to step 2.

Simulation Result

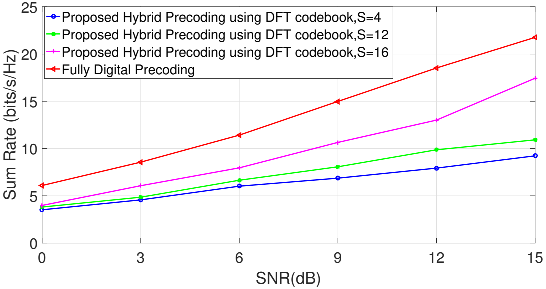


Figure: Sum Rate vs SNR, $M = N = 16, K = 4$

- ULA of transmit antennas $d = \lambda/2$
- $N_{cl} = 6, N_{ray} = 8$ AoD∼Laplacian, mean of $\phi_{m_p} \sim \mathcal{U}[-\pi, \pi)$, $\sigma_\phi = 7.5^o$
- $\zeta = 10^{-3}$
- $\lambda_L = 0$ & $\lambda_U = 100$.

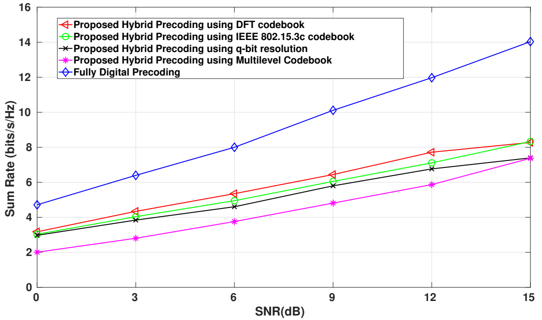


Figure: Sum Rate vs SNR, $M = N = 16, S = 4, K = 2$

- ULA of transmit antennas $d = \lambda/2$
- $N_{cl} = 6, N_{ray} = 8$ AoD$\sim$Laplacian, mean of $\phi_{m_p} \sim \mathcal{U}[-\pi, \pi)$, $\sigma_\phi = 7.5^o$
- $\zeta = 10^{-3}$
- $\lambda_L = 0$ & $\lambda_U = 100$.

Future Work

- In the future work we will optimize the codebook to get the best RF codebook among different codebooks.
- Also, we will check the robustness of the system when their is analog errors in RF precoder.

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Thank You