

Optimal Eigen Mode of MIMO

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For MIMO, in the frequency domain for a fixed frequency we have the transmit signal $X \in \mathbb{C}^M$ and receive signal $Y \in \mathbb{C}^N$ and the channel matrix $H \in \text{Hom}(\mathbb{C}^M, \mathbb{C}^N)$ related by

$$Y = HX \quad (1)$$

Our aim is to find an X subject to an energy constraint maximizes Y given H .

Assume the rank of H is r , we apply compact SVD on H to get

$$H = UDV^* \quad (2)$$

where $U \in \text{Hom}(\mathbb{C}^r, \mathbb{C}^N)$, $V \in \text{Hom}(\mathbb{C}^r, \mathbb{C}^M)$ satisfying $U^*U = I_N$ and $V^*V = I_M$, and

$$D = \text{diag}\{\sigma_1, \dots, \sigma_r\}$$

is a the diagonal matrix of singular values of H .

With proper pre-processing

$$X = VS$$

and post-processing

$$Z = U^*Y$$

we have

$$Z = U^*UDV^*VS = DS$$

which is a group of r parallel scalar channels without interfering with each other.

Claim 1. Pre-multiplying U^* and V preserve energy.

Proof.

$$X^*X = S^*V^*VS$$

It follows from

$$V^*V = I_M$$

The proof for U^* involves a little bit more. We have

$$Z^*Z = Y^*UU^*Y$$

We partition U into column vectors

$$U = [u^1, \dots, u^r]$$

where $u^i \in \mathbb{C}^N$ being mutually orthogonal. It follows from equation 1 and 2 that $\exists y^i \in \mathbb{C}$ s.t.

$$Y = \sum_{i=1}^r y_i u^i$$

Hence

$$\begin{aligned} Y^*UU^*Y &= \left(\sum_{i=1}^r y_i^* (u^i)^* \right) \left(\sum_{j=1}^r u^j (u^j)^* \right) \left(\sum_{k=1}^r y_k u^k \right) \\ &= \sum_{i,j,k} y_i^* y_k ((u^i)^* u^j) ((u^j)^* u^k) \\ &= \sum_{i,j,k} y_i^* y_k \delta_i^j \delta_j^k \\ &= \sum_{i=1}^r |y_i|^2 = Y^*Y \end{aligned}$$

which completes the proof. \square

Now our goal boils down to finding an S subject to an energy constraint maximizes Z given D , which is a convex optimization problem

$$\begin{aligned} &\text{maximize} && s^* D^2 s \\ &\text{subject to} && s^* s \leq 1 \end{aligned} \tag{3}$$

However, for $s \in \mathbb{C}^r$, the objective function is not differentiable. To see this, we need to take a detour to discuss the condition of differentiability of operators between complex vector spaces.

Pick any $f : \mathbb{C}^M \rightarrow \mathbb{C}^N$, then f is differentiable at $z \in \mathbb{C}^M$ if and only if there exists a linear operator $\nabla f(z) \in \text{Hom}(\mathbb{C}^M, \mathbb{C}^N)$ such that

$$\lim_{\Delta z \rightarrow 0} \frac{f(z + \Delta z) - f(z) - \nabla f(z)\Delta z}{\|\Delta z\|} = 0 \quad (4)$$

Expand f to be

$$f(z) = u(x, y) + iv(x, y) \quad (5)$$

where $z = x + iy$, and $x, y \in \mathbb{R}^M$, and $u, v : \mathbb{R}^M \times \mathbb{R}^M \rightarrow \mathbb{R}^N$.

Equation 4 implies the limit

$$\lim_{\Delta z \rightarrow 0} \frac{f(z + \Delta z) - f(z)}{\|\Delta z\|} \quad (6)$$

exists. Choose any $a \neq 0, a \in \mathbb{C}^M$ and a $t \in \mathbb{R}$. Let $\Delta z = ta$, then $\Delta z \rightarrow 0$ as $t \rightarrow 0$. Substitute 5 into 6. For Δz either being ta or ita , the limit should stay the same, which leads to a "quasi"-Cauchy-Riemann equations

$$\begin{aligned} u_x &= v_y \\ u_y &= -v_x \end{aligned}$$

where u_x is defined to be the unique linear operator in $\text{Hom}(\mathbb{R}^M, \mathbb{R}^N)$ such that

$$\lim_{\Delta x \rightarrow 0} \frac{u(x + \Delta x) - u(x) - u_x \Delta x}{\|\Delta x\|} = 0$$

and v_y, u_y, v_x are defined in similar ways.

We can see that the objective function of 3 is not differentiable. Indeed, $s^* D^2 s$ is a real-valued function which means $v_x = v_y = 0$, but this does not hold for u_x and u_y .

Note that restricting s on $\mathbb{R}_{\geq 0}^M$ does not change the optimal value of the objective function. It is not hard to see, by KKT condition, that the quadratic programming 3 restricted on $\mathbb{R}_{\geq 0}^M$ can achieve the optimal value

$$\max_s s^* D^2 s = \max_i \sigma_i^2$$

with the optimal point s whose i -th component is

$$s_i = \begin{cases} 1 & , i = \operatorname{argmax}_i \sigma_i \\ 0 & , \text{otherwise} \end{cases}$$

Then we extend the optimal points on \mathbb{C}^M . It is obvious that for any real diagonal matrix A , the vector given by

$$w = e^{jA}s$$

is also an optimal point.