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# Quasi-Orthogonal Beamforming in Near-Field Line-of-Sight MIMO Channel

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## Background & Motivation

**Ultra-high frequency:** millimeter-wave, terahertz

severe path loss to obstacles in non-line-of-sight (NLoS) links

**Ultra-massive MIMO:** near-field effect

Near-field spherical wavefront: angular and distance domains

⇒ **Near-field line-of-sight (LoS) MIMO channel: $\mathbf{H}$**

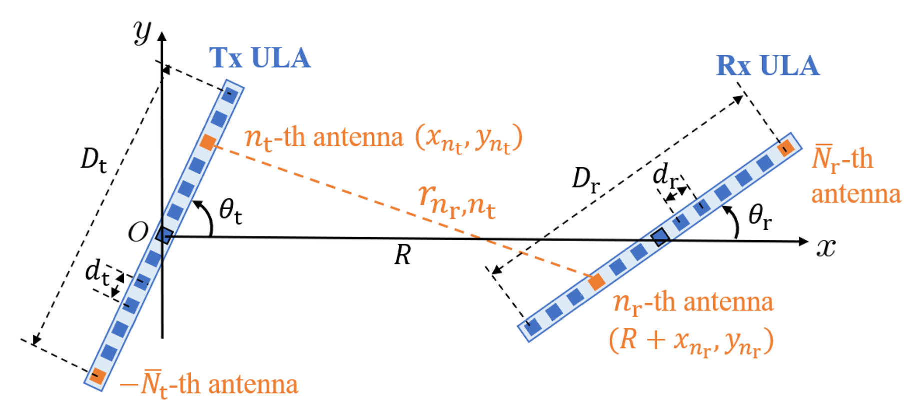
**Spatial multiplexing:**

- Far-field MIMO relies on the multipath provided by **scatterers**
- Near-field MIMO can exploit spatial multiplexing even in **LoS**

**Effective degrees-of-freedom (EDoF):** the number of high-quality orthogonal sub-channels (with significantly large channel gains)

**SVD ($\mathbf{H}=\mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^{\mathrm{H}}$) based beamforming:**

- an orthogonal basis (channel's left singular vectors) can be obtained to formulate beamforming matrix $\mathbf{V}$, which maps multiple data streams into orthogonal sub-channels $\mathbf{HV}$ for spatial multiplexing.
- **high computation and hardware complexity**




$$\mathbf{H}=\begin{bmatrix} h_{-\bar{N}_r,-\bar{N}_t} & \cdots & h_{-\bar{N}_r,\bar{N}_t} \\ \vdots & \ddots & \vdots \\ h_{\bar{N}_r,-\bar{N}_t} & \cdots & h_{\bar{N}_r,\bar{N}_t}\end{bmatrix}=\begin{bmatrix}\mathbf{h}^T_{-\bar{N}_r}\\ \vdots \\ \mathbf{h}^T_{\bar{N}_r}\end{bmatrix}$$

$$h_{n_r,n_t}=\frac{R}{r_{n_r,n_t}}\exp\left(-j\frac{2\pi}{\lambda}r_{n_r,n_t}\right)\overset{(a)}{\approx}\exp\left(-j\frac{2\pi}{\lambda}r_{n_r,n_t}\right)$$

**Fig. 1.** A geometric model of the LoS MIMO channel between uniform linear arrays (ULAs).

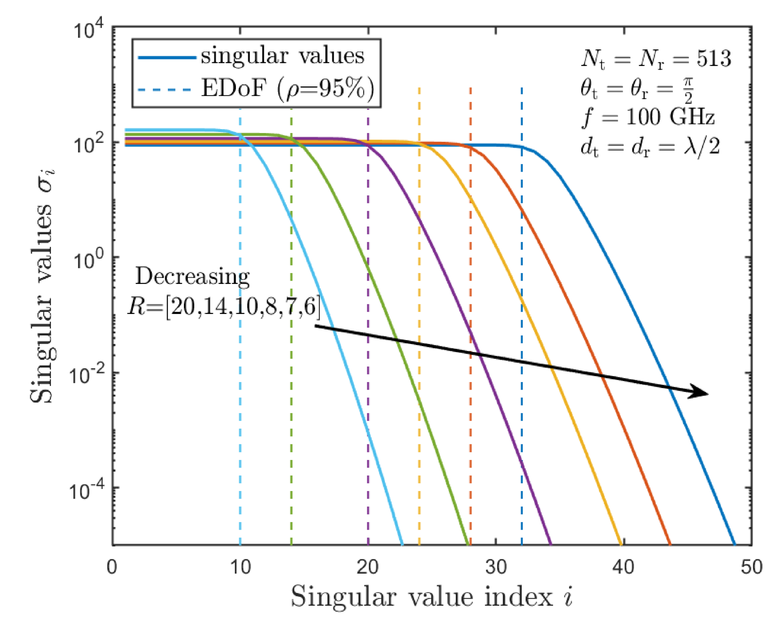



**Fig. 2.** Singular values of $\mathbf{H}$ for a pair of parallel 513 ULAs at 100 GHz with difference distances $R$, where $\sigma_i^2=\|\mathbf{Hv}_i\|^2$ is the $i$-th sub-channel gain.

## Quasi-Orthogonal (QO) Beamforming

The NF LoS MIMO channel exhibits high EDoF as the Tx can utilize the **NF spherical wave** to **resolve** different **Rx antennas**. The **number of resolvable Rx antennas** can be used to explicitly evaluate the **channel EDoF**. The **resolution** can be used to construct a set of **QO beamfocusing vectors**, which transforms the channel into the **QO sub-channels** for parallel data transmission.

### Channel structural characteristics: spherical wavefront

Tx can utilize the NF spherical wave to **resolve** different Rx antennas ($\ell$-th and $\ell'$-th Rx antennas)

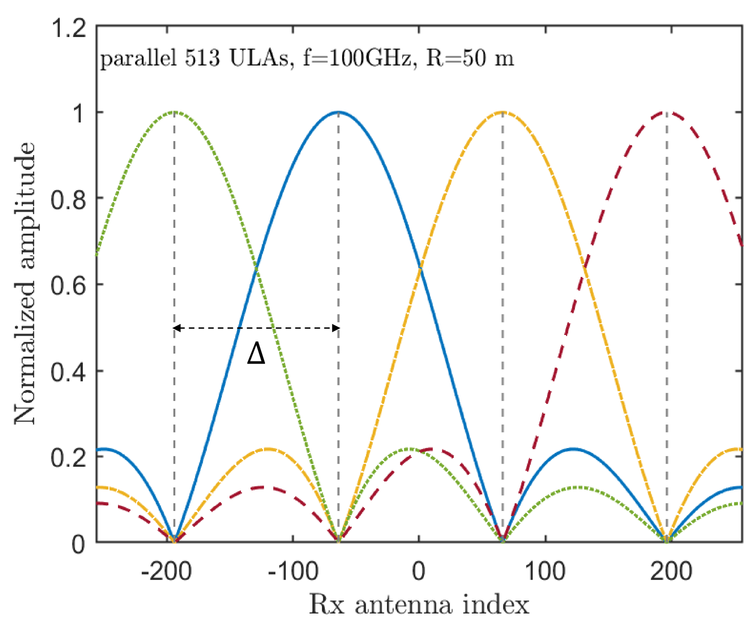



**Fig. 3.** Channel correlation $|\mathbf{h}^H_{\ell'}\mathbf{h}_\ell|$

**Resolution**

$$\Delta=\left\lceil\frac{\lambda R}{d_t d_r\sin\theta_t\sin\theta_r N_t}\right\rceil$$

$$\ell'-\ell=\iota\Delta\in\mathbb{Z}$$

Rx antenna indexes close to the zero-crossing points of the sinc function

**Quasi-Orthogonality:**

$$\frac{|\mathbf{h}^H_{\ell'}\mathbf{h}_\ell|}{||\mathbf{h}_{\ell'}||\,||\mathbf{h}_\ell||}<\epsilon$$

Quasi-Orthogonal Modes (QOMs): The channels from Tx antennas to any two different QOMs at Rx are QO (the number of QOMs: $N_{\mathrm{qom}}$)

$$\mathcal{Q}=\{\ell:\ell=\iota\Delta+\ell_0,\iota\in\mathbb{Z},\ell_0,\ell\in\{-\bar{N}_r,...,\bar{N}_r\}\}$$

Quasi-orthogonal beamfocusing vectors: $\hat{\mathbf{p}}_\ell,\ell\in\mathcal{Q}$

$$\hat{\mathbf{p}}_\ell=\frac{1}{\sqrt{N_t}}\mathbf{h}^*_\ell=\frac{1}{\sqrt{N_t}}[\exp(j\frac{2\pi}{\lambda}r_{\ell,-\bar{N}_t}),...,\exp(j\frac{2\pi}{\lambda}r_{\ell,\bar{N}_t})]^T$$

Quasi-orthogonal beamforming matrix: $\mathbf{P}\in\mathbb{C}^{N_t\times N_{\mathrm{qom}}}$

### Quasi-orthogonal beamspace channel: $\mathbf{H}_{e,\mathrm{QO}}=\mathbf{HP}\in\mathbb{C}^{N_r\times N_{\mathrm{qom}}}$

- Each column serves as a **QO sub-channel** $\mathbf{p}_i^H\mathbf{H}^H\mathbf{H}\mathbf{p}_{i'}\approx 0$ if $i\neq i'$
- $N_{\mathrm{qom}}\approx\mathrm{EDoF}(\mathbf{H})\triangleq N_e$ number of effective sub-channels (verified in simulations)
- Beamformer using **analog phase shifters**: each entry of $\mathbf{P}$ is constant-magnitude

### Quasi-orthogonal beamspace modulation (QO-BM):

Dynamically select $N_s$ sub-channels from $N_e$ ones for transmission $N_s=\min\{N_e,N_{rf}\}$

- **Conventional I/Q modulation:** transmit $N_s$ data streams over the selected sub-channels
- **Beam index modulation:** additional data stream over the selected sub-channel indexes

**Best beam selection (BBS):** the selected sub-channels are fixed as the best $N_s$ ones

$$\mathbf{y}=\beta\mathbf{HP}_{m_2}\mathbf{s}_{m_1}+\mathbf{w}=\beta\mathbf{HPE}_{m_2}\mathbf{s}_{m_1}+\mathbf{w}$$

Received signal, power, Tx beamforming, $\mathbf{H}_{e,\mathrm{QO}}$, Beam selection, Noise

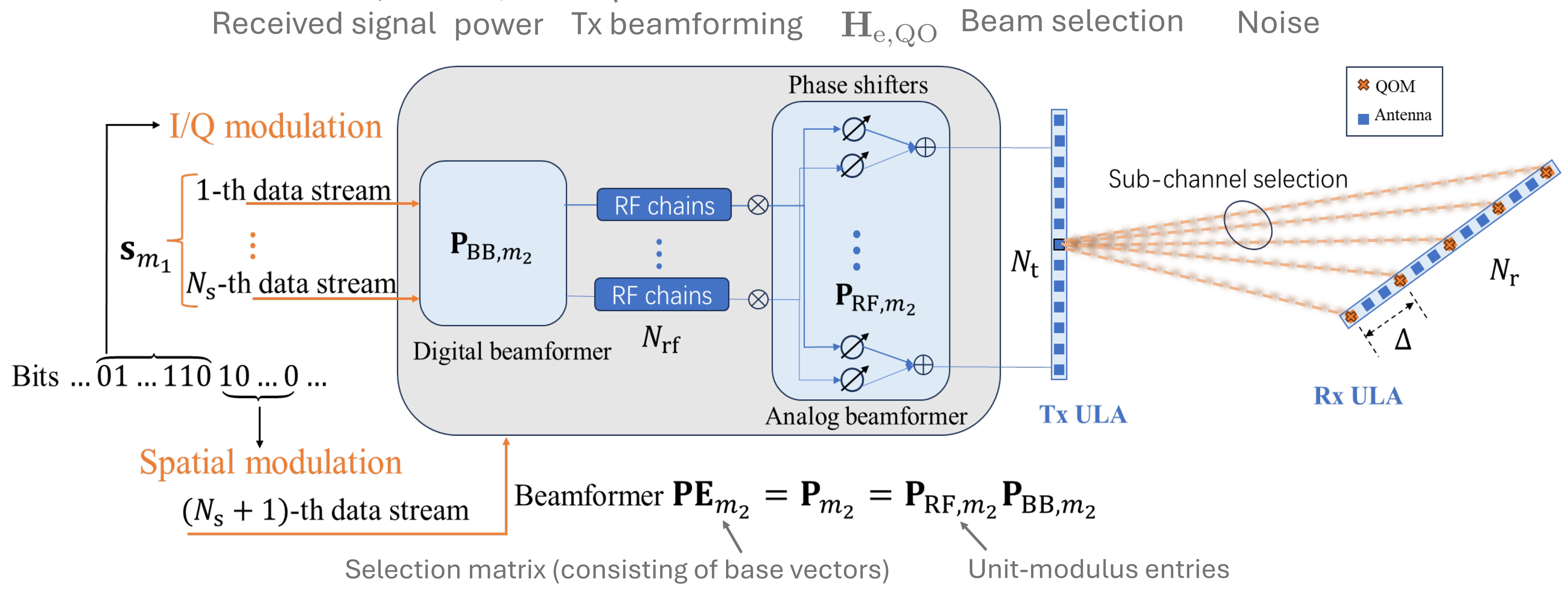



**Fig. 4.** Beamspace modulation ($\mathbf{E}_{m_2}\in\mathbb{R}^{N_e\times N_s}$ : choose $N_s$ sub-channels from all $N_e$ ones)

## Numerical results

**Effective sub-channels provided by SVD or QOMs:**

$\|\mathbf{Hv}_i\|^2$ vs $\|\mathbf{Hp}_i\|^2$ : Similar gain and number of effective sub-channels

**Data transmission: BM ≥ BBS**

BM increases the data rate by sub-channel index modulation

**BM based on SVD or QOMs:**

Rate: SVD-BM (hybrid) ≤ **QO-BM** ≈ SVD-BM (full digital)

Computation complexity: SVD-BM (hybrid) ≫ SVD-BM (full digital) ≫ **QO-BM**

Hardware complexity: SVD-BM (full digital) ≫ SVD-BM (hybrid) = **QO-BM**

(Number of RF chains)

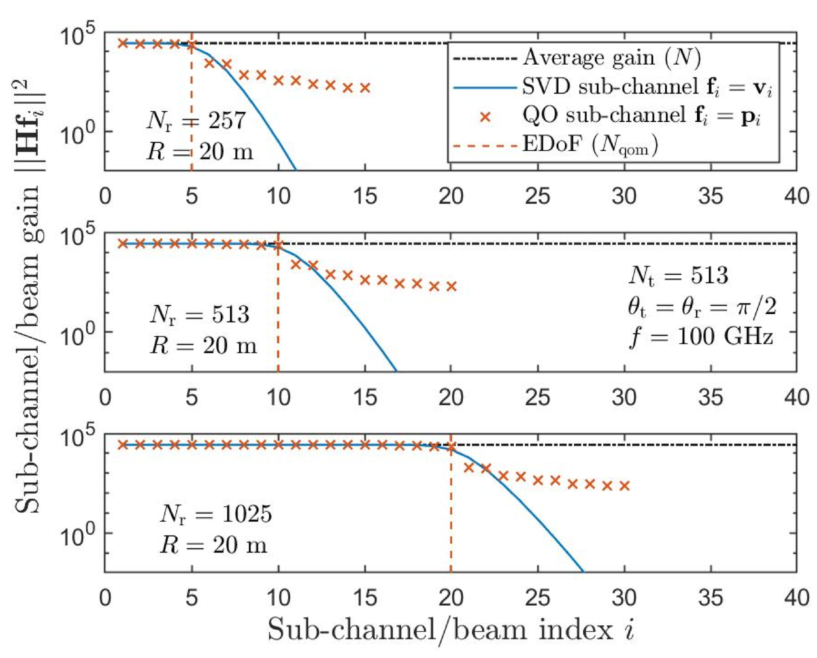



**Fig. 5.** Sub-channels provided by SVD and QOMs.

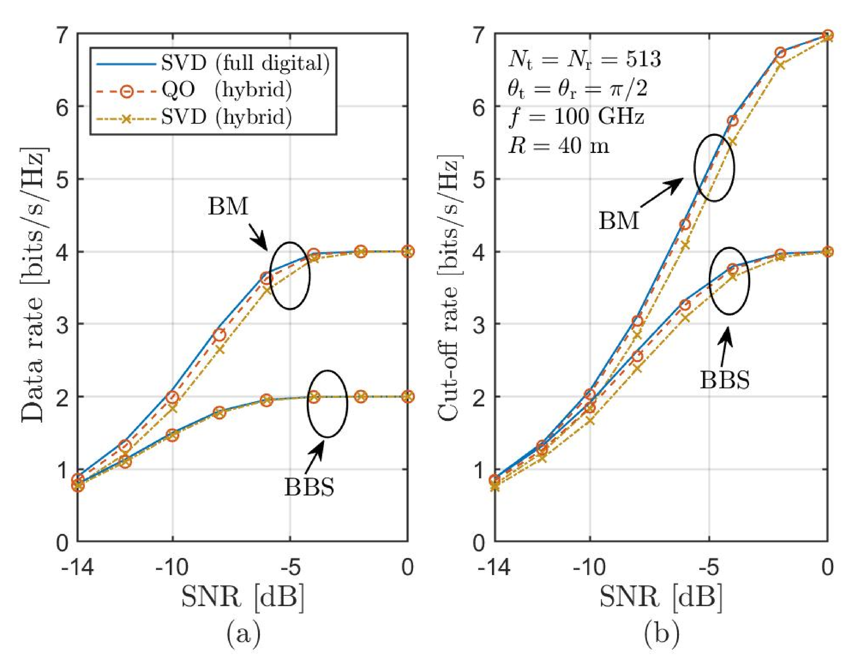



**Fig. 6.** Data rate at (a) $N_s=N_{rf}=1$ and (b) $N_s=N_{rf}=2$ (considering QAM in I/Q domain)

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