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Differential Beamspace MIMO for High-Dimensional Multiuser Communication

GlobalSIP 2015
December 14, 2015

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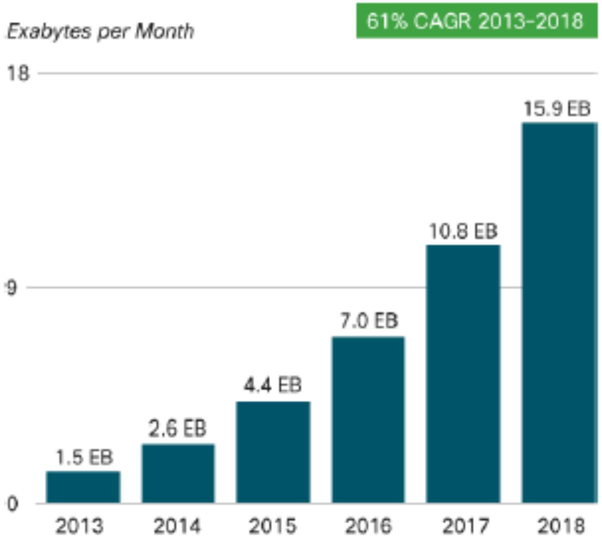
This work is partly supported by the NSF under grants ECCS-1247583 and IIP-1444962, and the Wisconsin Alumni Research Foundation.

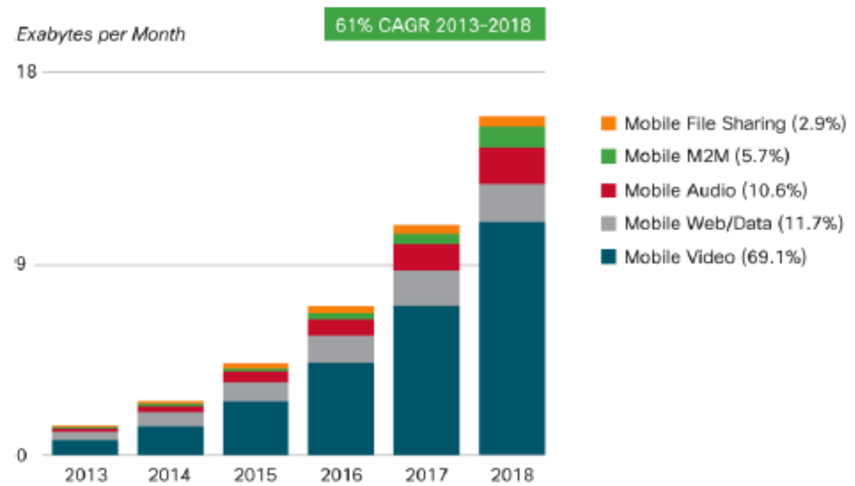
Explosive Growth in Wireless Traffic

Figure 1. Cisco Forecasts 15.9 Exabytes per Month of Mobile Data Traffic by 2018

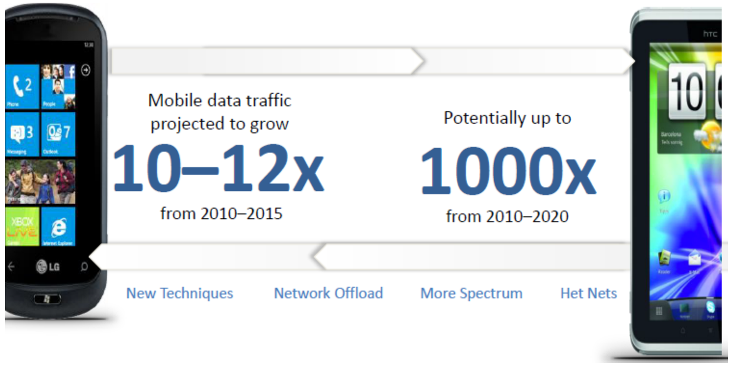


Source: Cisco VNI Mobile, 2014

Figure 10. Mobile Video Will Generate Over 69 Percent of Mobile Data Traffic by 2018



Figures in parentheses refer to traffic share in 2018.
Source: Cisco VNI Mobile, 2014



(Qualcomm)

Cm-Wave and Mm-wave Wireless: 10-300 GHz

A unique opportunity for addressing the wireless data challenge

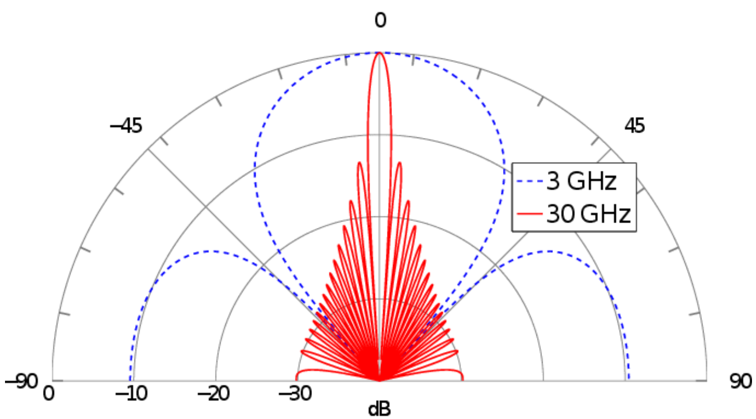
– Large bandwidths (GHz)

– High spatial dimension: short wavelength (1-30mm)

Compact high-dimensional multi-antenna arrays

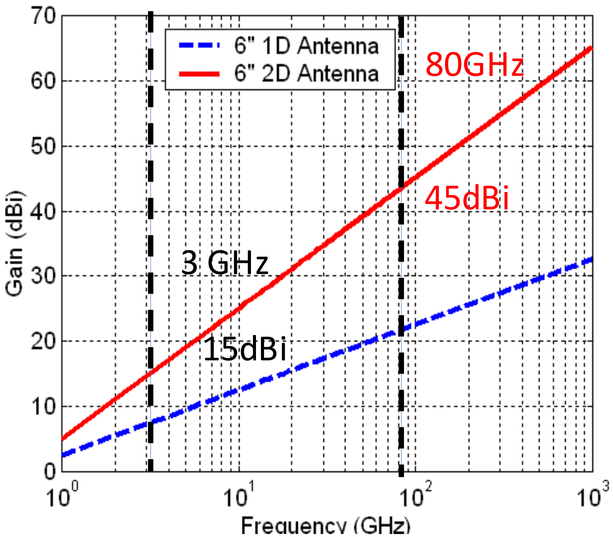
6” antenna: 6400-element antenna array (80GHz)

Highly directive narrow beams (dense spatial multiplexing)



Beamwidth: 35 deg @ 3GHz 2 deg @ 80GHz

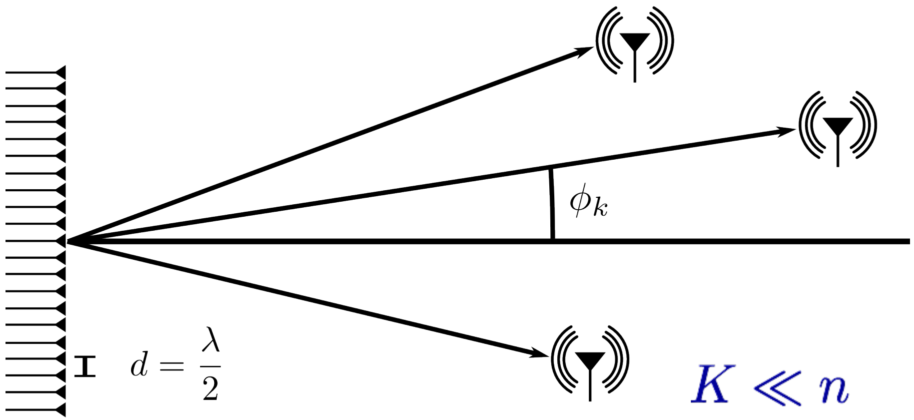
Large antenna gain



Contributions

- Key functionality: Electronic multi-beam steering & MIMO data multiplexing
- Goal: Design linear multiuser MIMO precoders for high-dimensional systems
- Challenge 1: Hardware & software complexity due to the high dimension
  - Beamspace MIMO – multiplexing data onto orthogonal spatial beams
  - Channel sparsity & beam selection: near-optimal dimensionality reduction
  - Analog beamforming: dramatic reduction in hardware complexity
- Challenge 2: Linear precoding typically requires coherent signaling
  - Requires phase/frequency synchronization between the TX/RX local oscillators
  - Limited by oscillator phase noise
  - Differential MIMO – enables MIMO spatial multiplexing with differential signaling
- Solution: Differential Beamspace MIMO (DB-MIMO) for multiuser systems

Multiuser System Model: Downlink



Mobile Stations (MSs)

Access Point (AP)
n-element
uniform linear array (ULA)

steering (TX)/response (RX) vector
(n-dimensional spatial sinusoid)

$$\mathbf{a}_n(\theta) = \begin{bmatrix} 1 \\ e^{-j2\pi\theta} \\ \vdots \\ e^{-j2\pi\theta(n-1)} \end{bmatrix}$$

Spatial frequency: $\theta = 0.5 \sin \phi$

Channel model: $\mathbf{h}_k = \mathbf{a}_n(\theta_k)$

RX signal at the k-th MS: $r_k = \mathbf{h}_k^H \mathbf{x} + \nu_k$

$K \times n$ MIMO system: $\mathbf{r} = \mathbf{H}^H \mathbf{x} + \boldsymbol{\nu}$ $\quad \mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_k]$

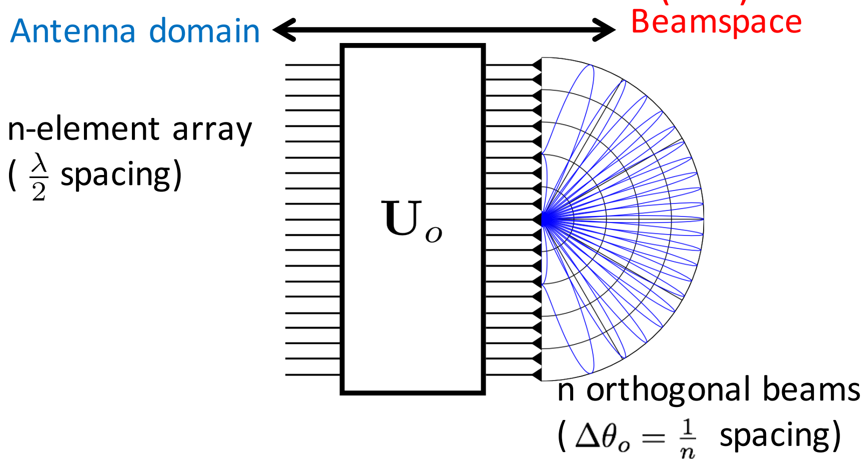
Linear Precoding: $\mathbf{x} = \mathbf{G}\mathbf{s}$

$\mathbf{r} = \mathbf{H}^H \mathbf{G}\mathbf{s} + \boldsymbol{\nu}$ $\quad \mathbf{s} = [s_1, s_2, \ldots, s_K]^T$, $\boldsymbol{\Lambda}_s = E[\mathbf{s}\mathbf{s}^H]$

$E\left[\|\mathbf{x}\|^2\right] = \mathrm{tr}(\mathbf{G}\boldsymbol{\Lambda}_s\mathbf{G}^H) \leq \rho$ (TX power constraint)

Beamspace MIMO & Channel Sparsity

Discrete Fourier Transform (DFT)

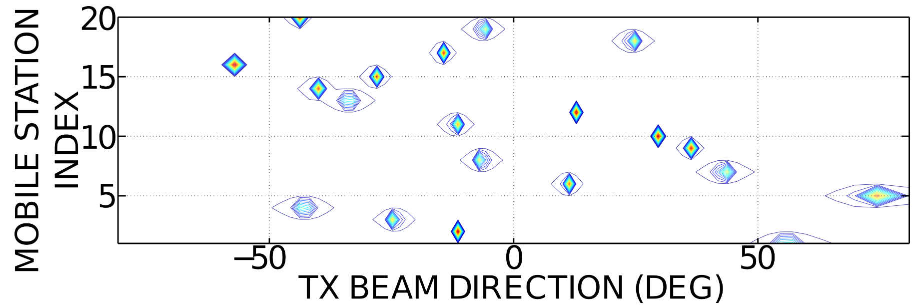


$$\mathbf{U}_o = [\mathbf{a}_n(i\Delta\theta_o)]_{i=0,\ldots,n-1}$$

Beamspace MIMO system equation

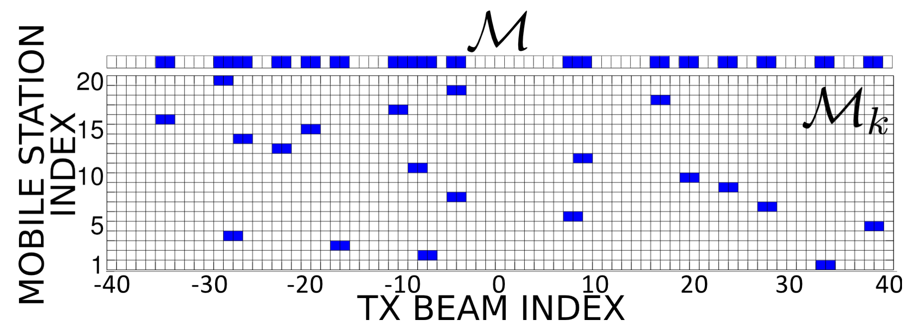
$$\mathbf{r} = \mathbf{H}_b^H \mathbf{G}_b \mathbf{s} + \boldsymbol{\nu} \qquad \mathbf{h}_{b,k} = \mathbf{U}_o^H \mathbf{h}_k$$

$$\mathbf{H}_b = [\mathbf{h}_{b,1}, \mathbf{h}_{b,k}, \ldots, \mathbf{h}_{b,K}]$$



Contour plot of $|\mathbf{H}_b^H|^2$ for a ULA with n=81 for K = 20 MSs

Select m strongest beams (m-beam mask)



Sparsity masks for K=20 using a 2-beam mask

$p \times K$ low dimensional system ($p \approx mK$)

$$\mathbf{r} = \tilde{\mathbf{H}}_b^H \tilde{\mathbf{G}}_b \mathbf{s} + \boldsymbol{\nu} \qquad \tilde{\mathbf{H}}_b = [\mathbf{H}_b(\ell, :)]_{\ell \in \mathcal{M}}$$

Differential SISO vs Differential MIMO

Assumption phase offset ϕ_o remains constant (or varies slowly)

- Information encoded in the phase $\Delta\phi$ difference between symbols

$$s = s(t) \qquad s_\tau = s(t-T)$$

$$s = Ae^{j\phi} = e^{j\Delta\phi} s_\tau$$

$$r = e^{j\phi_o} s + \nu \qquad r_\tau = e^{j\phi_o} s_\tau + \nu_\tau$$

SISO Differential measurement: $rr_\tau^* = ss_\tau^* + s\nu_\tau^* + \nu s_\tau^* + \nu\nu_\tau^* = e^{j\Delta\phi} + w$

MIMO (Special case 2x2 example)

Assumption MIMO channel $\mathbf{H}$ remains constant (or varies slowly)

$$\mathbf{s} = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \qquad \mathbf{s}_\tau = \begin{bmatrix} s_{1\tau} \\ s_{2\tau} \end{bmatrix} \qquad s_\ell = Ae^{j\phi_\ell} = e^{j\Delta\phi_\ell} s_\tau \qquad \mathbf{r} = \mathbf{H}\mathbf{s} + \boldsymbol{\nu} \qquad \mathbf{r}_\tau = \mathbf{H}\mathbf{s}_\tau + \boldsymbol{\nu}_\tau$$

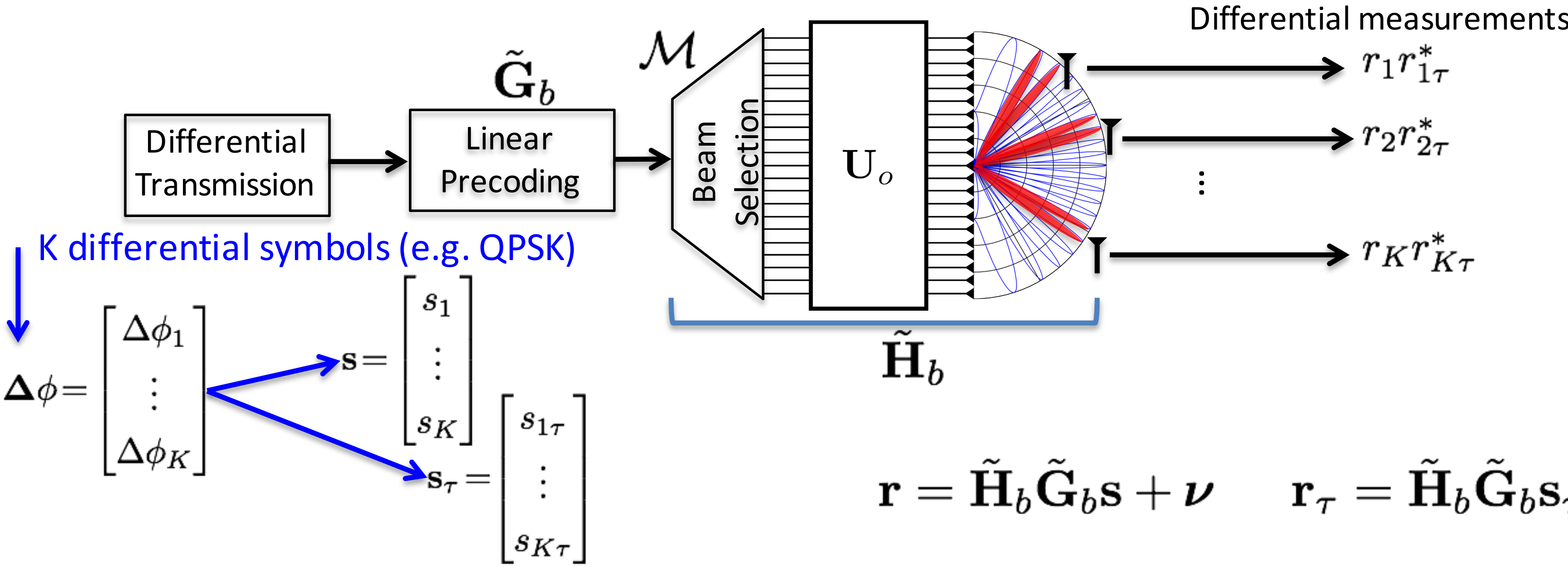
MIMO Differential measurement: $\mathbf{z} = \mathrm{vec}(\mathbf{r}\mathbf{r}_\tau^H) = \begin{bmatrix} r_1 r_{1\tau}^* \\ r_2 r_{1\tau}^* \\ r_1 r_{2\tau}^* \\ r_2 r_{2\tau}^* \end{bmatrix} = \mathbf{H}_d \boldsymbol{\chi} + \mathbf{w} \qquad \boldsymbol{\chi} = \mathrm{vec}(\mathbf{s}\mathbf{s}_\tau^H) = \begin{bmatrix} s_1 s_{1\tau}^* \\ s_2 s_{1\tau}^* \\ s_1 s_{2\tau}^* \\ s_2 s_{2\tau}^* \end{bmatrix}$

$$\mathbf{H}_d = (\mathbf{H}^* \otimes \mathbf{H}) = \begin{bmatrix} |h_{11}|^2 & h_{11}^* h_{12} & h_{12}^* h_{11} & |h_{12}|^2 \\ h_{11}^* h_{21} & h_{11}^* h_{22} & h_{12}^* h_{21} & h_{12}^* h_{22} \\ h_{21}^* h_{11} & h_{21}^* h_{12} & h_{22}^* h_{11} & h_{22}^* h_{12} \\ |h_{21}|^2 & h_{21}^* h_{22} & h_{22}^* h_{21} & |h_{22}|^2 \end{bmatrix}$$

Differential transmit vector elements corresponding to the differential symbols

Multiuser DB-MIMO System Model

$p \times K$ MIMO system induced via beam selection



$$\mathbf{r} = \tilde{\mathbf{H}}_b \tilde{\mathbf{G}}_b \mathbf{s} + \boldsymbol{\nu} \qquad \mathbf{r}_\tau = \tilde{\mathbf{H}}_b \tilde{\mathbf{G}}_b \mathbf{s}_\tau + \boldsymbol{\nu}_\tau$$

DB-MIMO System Equation

$$\mathbf{z} = \mathrm{vec}(\mathbf{r}\mathbf{r}_\tau^H) = \tilde{\mathbf{H}}_{b,d}^H \tilde{\mathbf{G}}_{b,d}\, \boldsymbol{\chi} + \mathbf{w}$$

DB-MIMO channel: $\tilde{\mathbf{H}}_{b,d} = (\tilde{\mathbf{H}}_b^* \otimes \tilde{\mathbf{H}}_b)$

DB-MIMO precoder: $\tilde{\mathbf{G}}_{b,d} = (\tilde{\mathbf{G}}_b^* \otimes \tilde{\mathbf{G}}_b)$

MS differential measurements: $r_k r_{k\tau}^*$ ⟺ Elements of $\boldsymbol{\chi}$: $s_k s_{k\tau}^* = e^{j\Delta\phi_k}$

Quasi-Coherent DB-MIMO Precoders

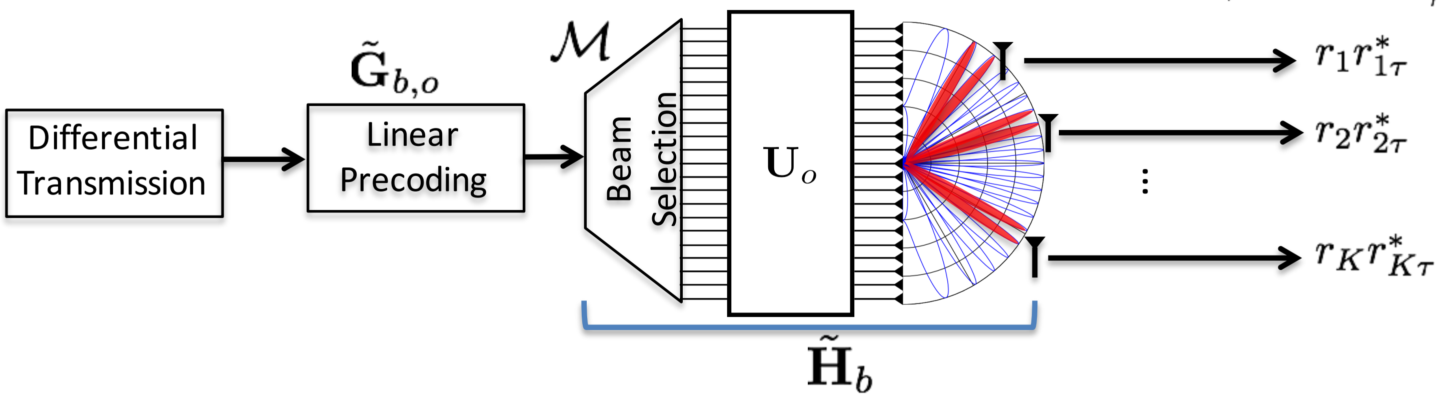
MU-MIMO precoders (based on the coherent channel)

$$\tilde{\mathbf{G}}_b = \alpha \mathbf{F} = \alpha\,[\mathbf{f}_1, \mathbf{f}_2, \ldots, \mathbf{f}_K] \qquad \mathbf{F}_{MF} = \tilde{\mathbf{H}}_b \qquad \mathbf{F}_{WF} = (\tilde{\mathbf{H}}_b \tilde{\mathbf{H}}_b^H + \zeta)^{-1} \tilde{\mathbf{H}}_b \ , \ \zeta = \frac{\sigma^2 K}{\rho}$$

Quasi-Coherent channel: what can be estimated at the AP

$$\tilde{\mathbf{H}}_b = \tilde{\mathbf{H}}_{b,o} \mathbf{\Lambda}_\psi \qquad \mathbf{\Lambda}_\psi = \mathrm{diag}(e^{j\psi_1}, \ldots, e^{j\psi_K})$$

Quasi-coherent precoder applied at the AP: $\tilde{\mathbf{G}}_{b,o} = \tilde{\mathbf{G}}_b \mathbf{\Lambda}_\psi^*$



$$\mathbf{r} = \tilde{\mathbf{H}}_b \tilde{\mathbf{G}}_b \mathbf{\Lambda}_\psi^* \mathbf{s} + \boldsymbol{\nu} \qquad \mathbf{r}_\tau = \tilde{\mathbf{H}}_b \tilde{\mathbf{G}}_b \mathbf{\Lambda}_\psi^* \mathbf{s}_\tau + \boldsymbol{\nu}$$

Does not affect differentially encoded information

Quasi-Coherent Channel Estimation

Assumption: system operates in a TDD mode with channel estimation performed during uplink

Noise-free uplink differential measurements

$$\tilde{\mathbf{r}}_b = \tilde{\mathbf{H}}_b \mathbf{x} \qquad \tilde{\mathbf{r}}_{b\tau} = \tilde{\mathbf{H}}_b \mathbf{x}_\tau$$

$$\mathbf{z} = \mathrm{vec}(\tilde{\mathbf{r}}_b \tilde{\mathbf{r}}_{b\tau}^H) = (\tilde{\mathbf{H}}_b^* \otimes \tilde{\mathbf{H}}_b)\mathrm{vec}(\mathbf{x}\mathbf{x}_\tau^H) = \tilde{\mathbf{H}}_{b,d}\mathcal{X} + \mathbf{w}$$

$$\tilde{\mathbf{H}}_{b,d} = [\tilde{\mathbf{h}}_{b,1}^* \otimes \tilde{\mathbf{H}}_b,\ \tilde{\mathbf{h}}_{b,2}^* \otimes \tilde{\mathbf{H}}_b,\ \ldots,\ \tilde{\mathbf{h}}_{b,K}^* \otimes \tilde{\mathbf{H}}_b]$$

$$[\tilde{\mathbf{h}}_{b,1}^* \otimes \tilde{\mathbf{h}}_{b,1},\ \tilde{\mathbf{h}}_{b,1}^* \otimes \tilde{\mathbf{h}}_{b,2}, \ldots,\ \tilde{\mathbf{h}}_{b,1}^* \otimes \tilde{\mathbf{h}}_{b,K}]$$

Only need to estimate of the quasi-coherent channel $\tilde{\mathbf{H}}_{b,o}$ (sub-matrix of $\tilde{\mathbf{H}}_{b,d}$)

Quasi-coherent channel estimation

Training for the k[th] MS: $\mathbf{x} = \mathbf{x}_\tau = \mathbf{e}_{K,k}$

Send one on consecutive symbols

$$\mathbf{z} = (\tilde{\mathbf{h}}_{b,k}^* \otimes \tilde{\mathbf{h}}_{b,k}^H) = \left[\tilde{h}_{b,k}^*(\ell)\tilde{\mathbf{h}}_{b,k}^T\right]_{\ell\in\mathcal{M}}^T$$

$$\ell = m_k$$

$$\tilde{\mathbf{z}} = \tilde{h}_{b,k}^*(m_k)\tilde{\mathbf{h}}_{b,k} \qquad \tilde{z}(m_k) = |\tilde{h}_{b,k}(m_k)|^2 \Rightarrow \tilde{\mathbf{h}}_{b,k,o} = \frac{1}{\sqrt{|\tilde{z}(m_k)|}}\tilde{\mathbf{z}} = \tilde{\mathbf{h}}_{b,k} e^{-j\angle \tilde{h}_{b,k}(m_k)}$$

Repeat sequentially for all K MSs

$$\tilde{\mathbf{H}}_{b,o} = [\tilde{\mathbf{h}}_{b,1,o},\ \tilde{\mathbf{h}}_{b,2,o}, \ldots,\ \tilde{\mathbf{h}}_{b,K,o}] = \tilde{\mathbf{H}}_b \mathbf{\Lambda}_\psi^* \qquad \mathbf{\Lambda} = \mathrm{diag}(e^{-j\angle\tilde{h}_{b,k}(m_1)}, \ldots, e^{-j\angle\tilde{h}_{b,k}(m_K)})$$

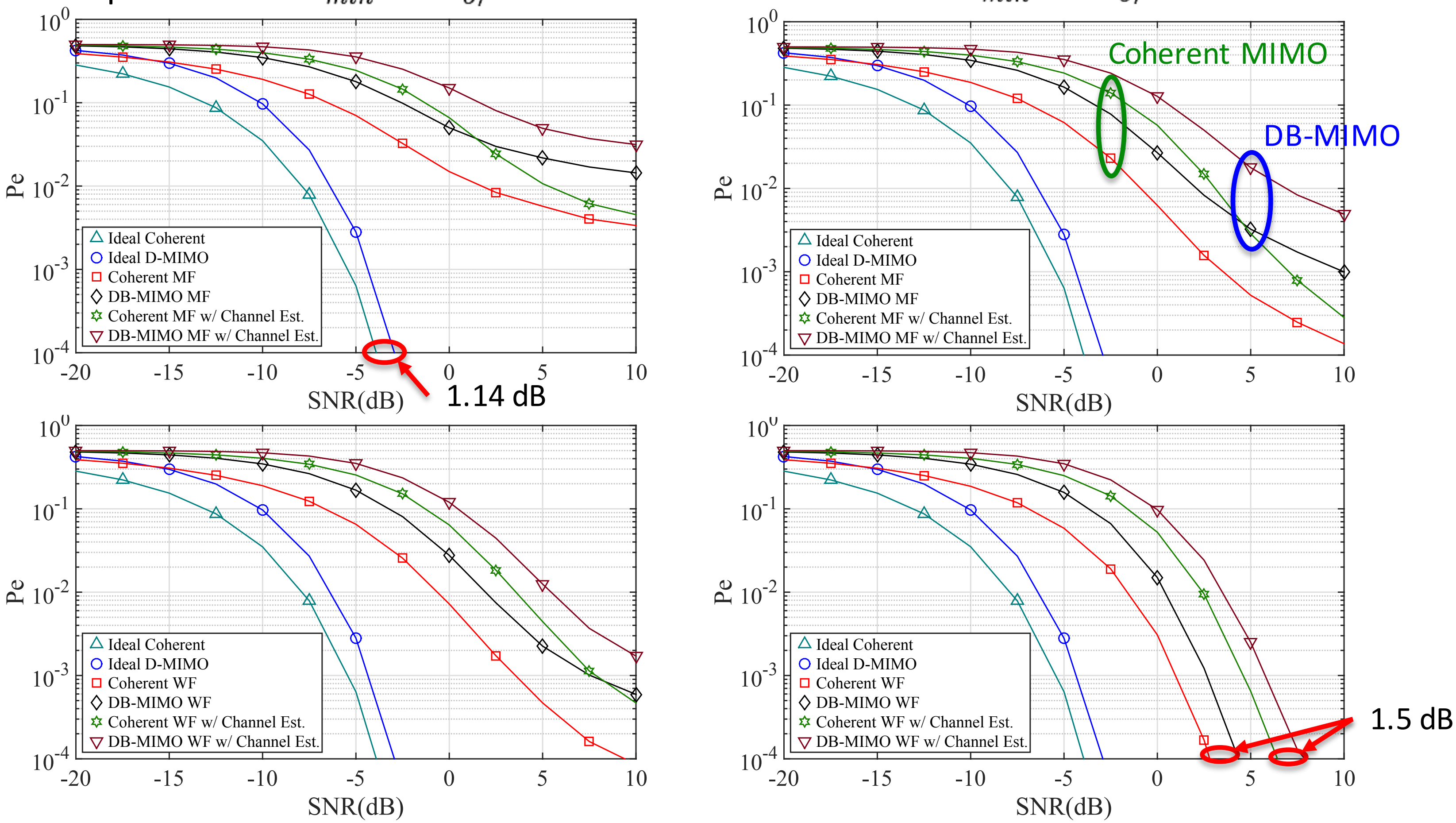
Numerical Results

AP equipped with a ULA of dimension n=81 (6” linear antenna at 80 GHz)
K=20 MSs, p≈40
P_e computed numerically over 1,000,000 BPSK symbol vectors
Channel realization (random MS locations $\{\theta_k\}_{k=1}^{K}$) changes every 200 symbols

Minimum MS Separation: $\Delta\theta_{min} = \Delta\theta_o/4$ | $\Delta\theta_{min} = \Delta\theta_o/2$

Matched Filter

Wiener Filter



Conclusions

- Multiuser DB-MIMO transceiver architectures
  - Beamspace MIMO techniques for near-optimal complexity reduction
  - Differential MIMO extended to multiuser setting
  - Relaxes phase coherence requirements on multiuser systems
- TDD Quasi-coherent channel estimation procedure presented
- Numerical results: minimal performance loss compared to coherent counterparts

Thank You / Questions ?