香港中文大學（深圳）
The Chinese University of Hong Kong, Shenzhen

Transceiver Optimization in Full-Duplex Multi-User Networks

Tsung-Hui Chang（张纵辉）
SSE, CUHK(SZ)
MOA, 2018

Joint work with Yafeng Liu (CAS) and Shih-Chun Lin (NTUST)

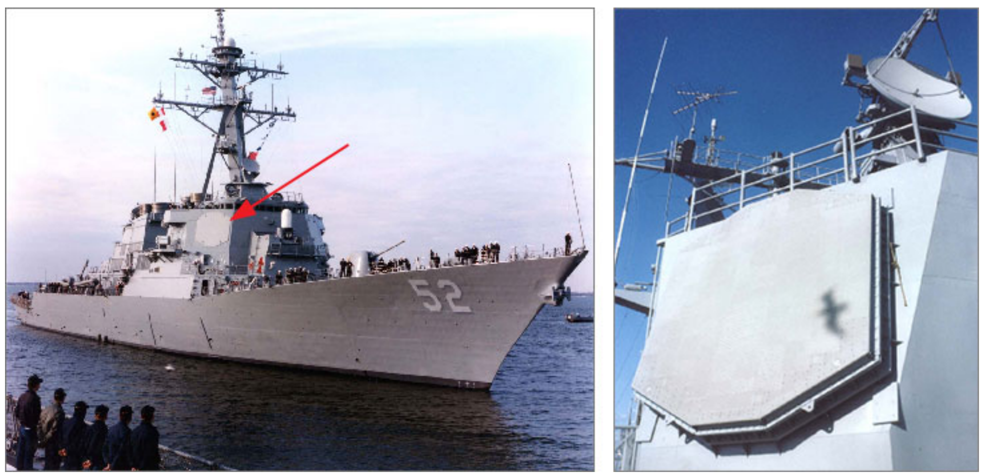
Outline

- Transmit and receive beamforming optimization in half-duplex systems
- Full-duplex (FD) communications
- Transceiver design for multi-user FD systems
- Global solution and efficient suboptimal solution
- Numerical results

Multi-antenna Communications

- Key to modern communication systems

Multi-antenna base station

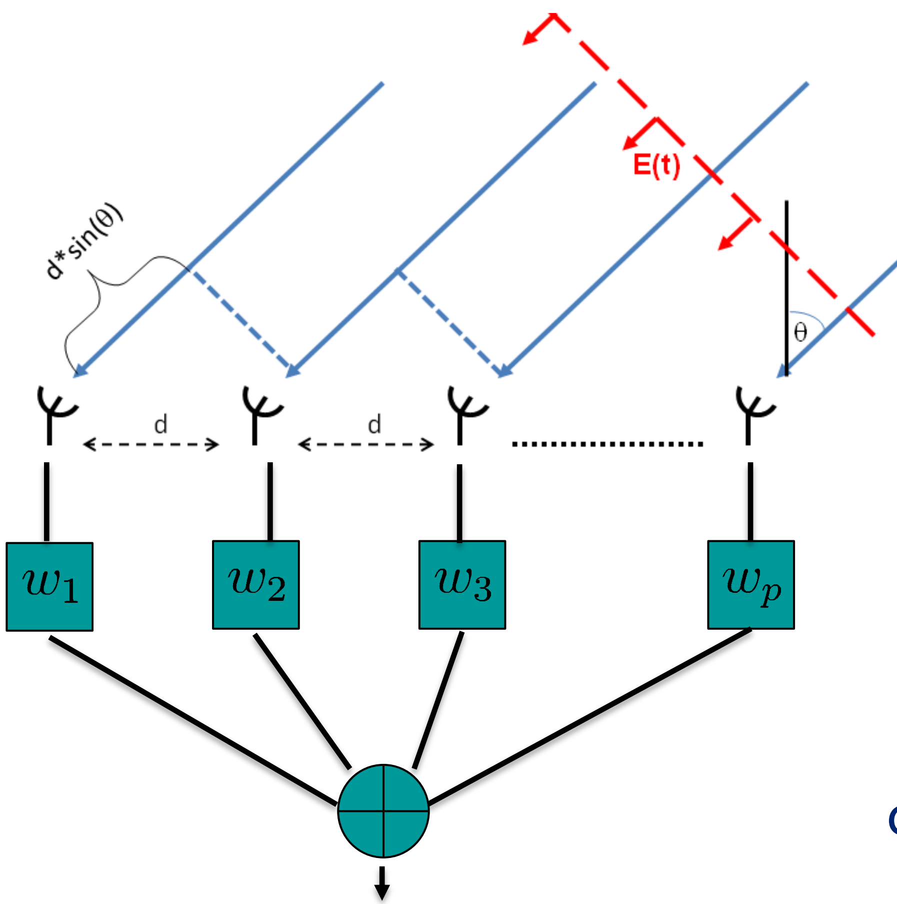


Radar array on Destroyer

Massive MIMO for 5G

Array Signal Model

- Signal reception via antenna array



$$\mathbf{x}(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_p(t) \end{bmatrix}$$

$$= \begin{bmatrix} 1 \\ e^{j2\pi \frac{\sin(\theta_0)d}{\lambda}} \\ \vdots \\ e^{j2\pi \frac{\sin(\theta_0)d}{\lambda}(p-1)} \end{bmatrix} s(t) + \mathbf{z}(t)$$

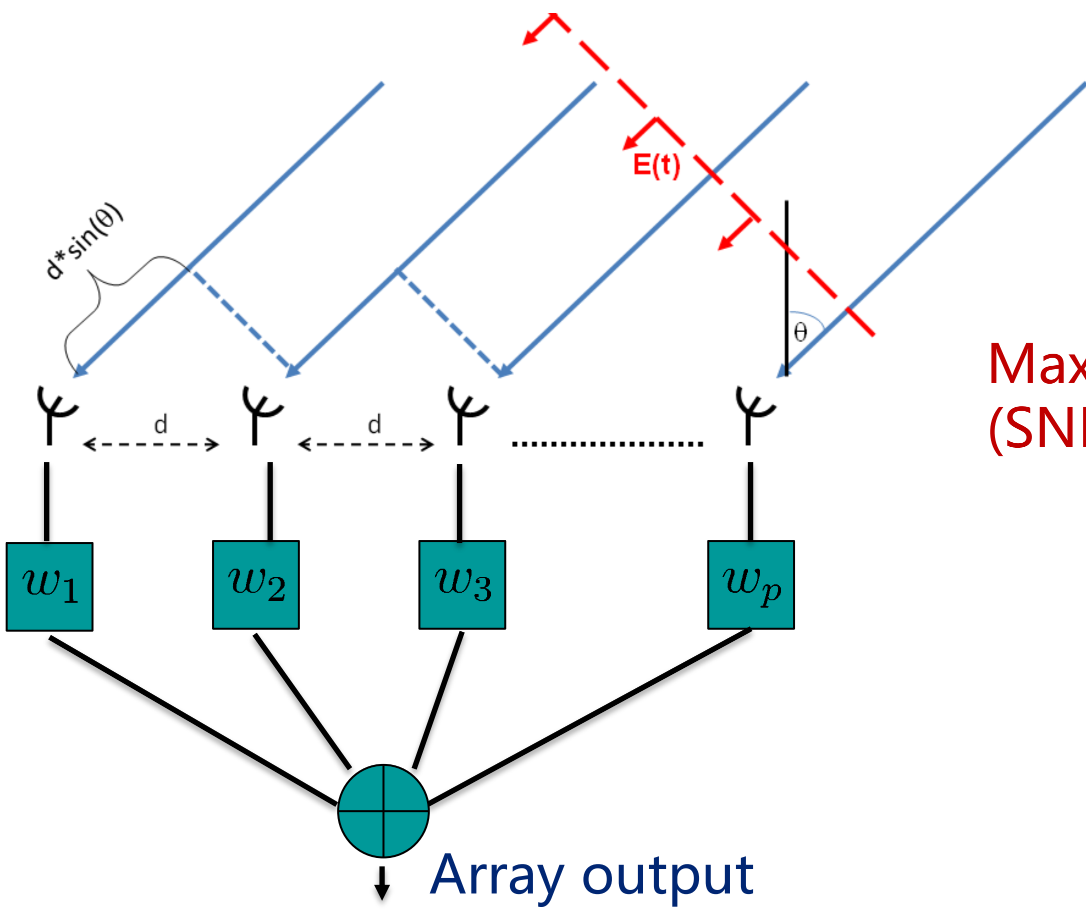
Additive noise

$$= \mathbf{a}(\theta_0)s(t) + \mathbf{z}(t)$$

channel vector

Array Signal Model

- Linear processing



Array output

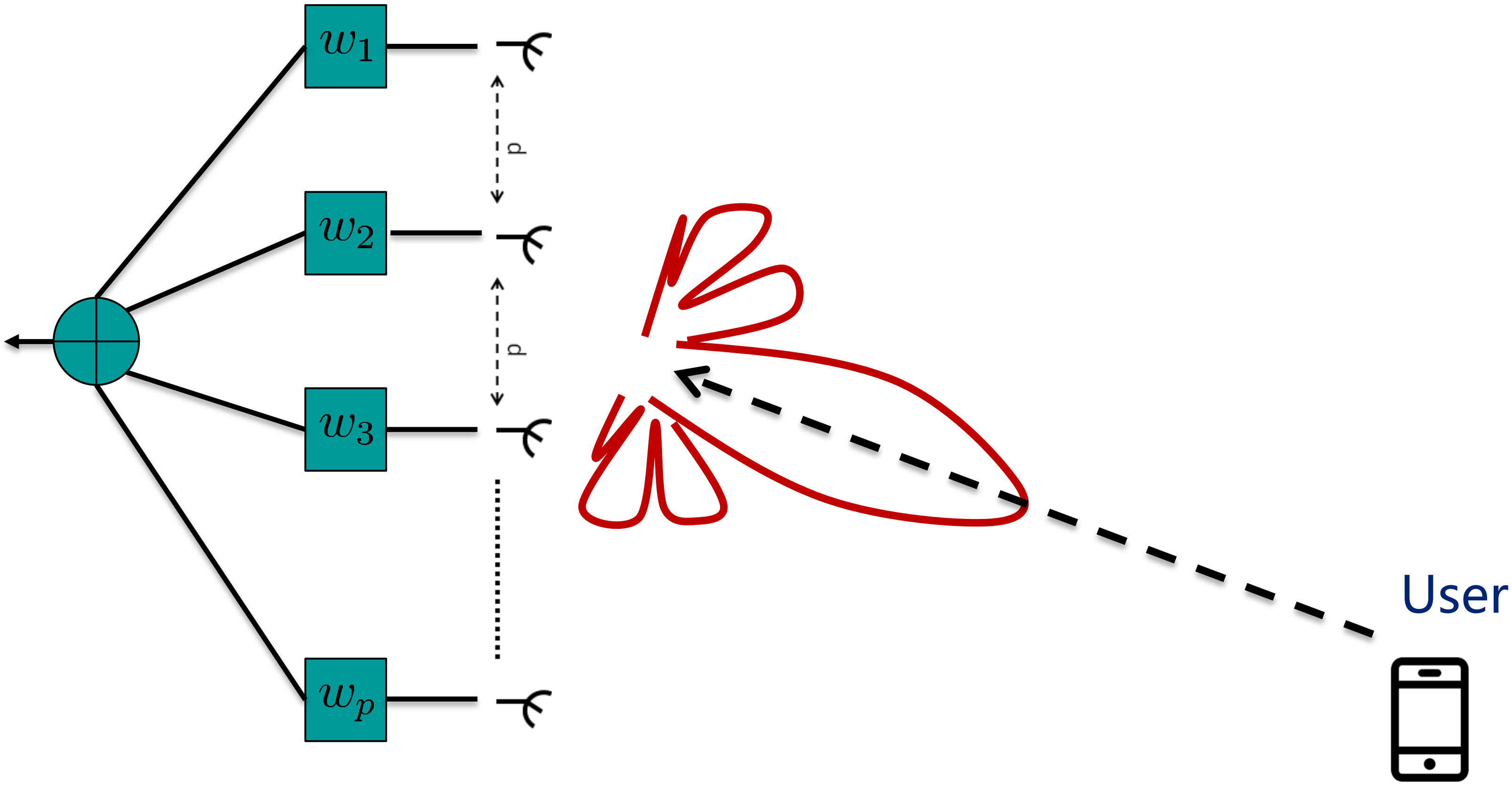
$$= \mathbf{w}^H(\mathbf{a}(\theta_0)s(t) + \mathbf{z}(t))$$

Maximum Signal-to-noise ratio (SNR) is achieved when

$$\mathbf{w} = \mathbf{a}(\theta_0)$$

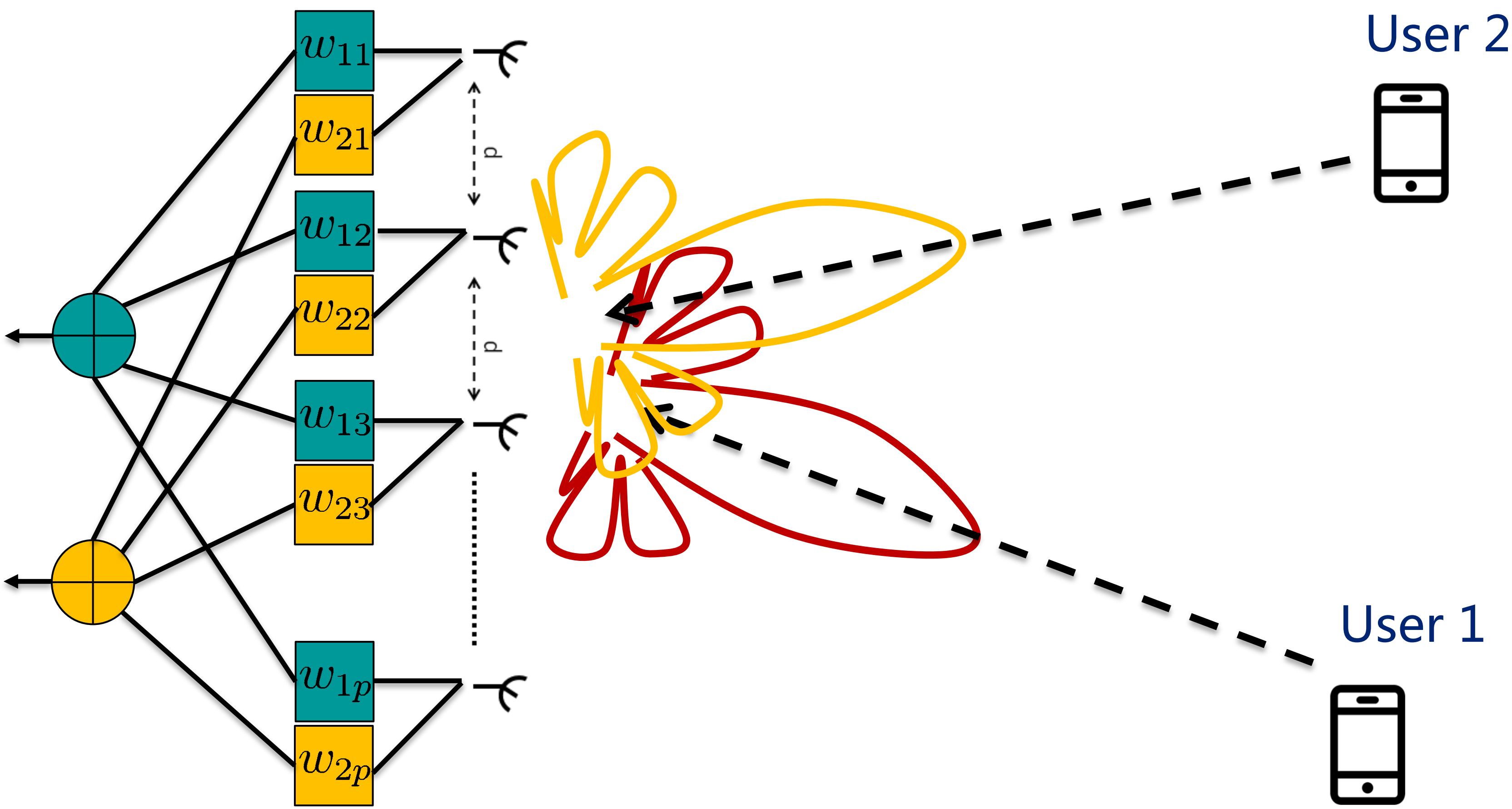
Array Signal Model: Beamforming

- Array response: Suppose $\theta_0 = 30^o$



Array Signal Model: Beamforming

- Array response: Suppose $\theta_1 = 30^o,\ \theta_2 = -30^o$



Multi-User Uplink

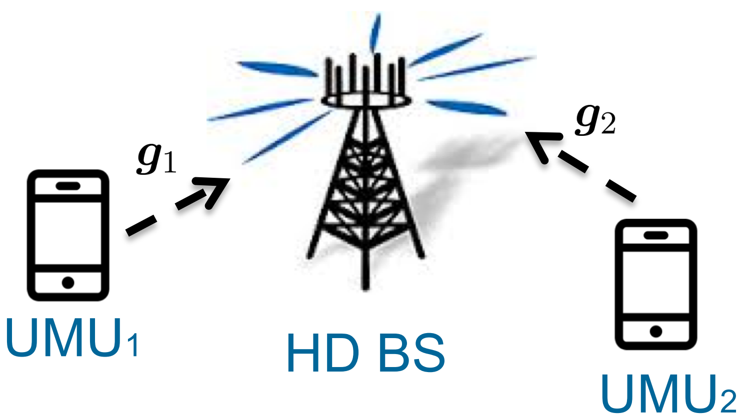
- Signal model

Received signal at the BS

$$\boldsymbol{y}^{\mathrm{U}}(t) = \sum_{\ell=1}^{L} \boldsymbol{g}_\ell \sqrt{p_\ell^{\mathrm{U}}} s_\ell^{\mathrm{U}}(t) + \boldsymbol{z}^{\mathrm{U}}(t).$$

Receive beamformer

$\boldsymbol{v}_1, \boldsymbol{v}_2$



Beamforming output

$$\boldsymbol{v}_\ell^H \boldsymbol{y}^{\mathrm{U}}(t),\ \ell = 1, \ldots, L$$

Signal-to-interference-plus-noise ratio (SINR)

$$\frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2}{\sum_{j\neq\ell}^{L} p_j^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_j|^2 + \sigma_z^2 \|\boldsymbol{v}_\ell\|_2^2},\quad \ell = 1, \ldots, L$$

Optimal Receive Beamforming

- Design problem

$$\text{(HUL)} \quad \min_{\{\boldsymbol{v}_\ell\},\{p_\ell^{\mathrm{U}}\geq 0\}} \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}$$

$$\text{s.t.} \quad \frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2}{\sum_{j\neq\ell}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \boldsymbol{g}_j \boldsymbol{g}_j^H \boldsymbol{v}_\ell + \sigma_z^2 \|\boldsymbol{v}_\ell\|_2^2} \geq \gamma_\ell^{\mathrm{U}}, \; \ell \in \mathcal{L},$$

where γ_ℓ^{U} is the target SINR for user ℓ.

- Non-convex, but is polynomial time solvable [GSSBO'10].

[GSSBO'10] A. B. Gershman, N. D. Sidiropoulos, S. Shahbazpanahi, M. Bengtsson, and B. Ottersten, "Convex optimization-based beamforming," IEEE Signal Process. Mag., pp. 62–75, May 2010.

Optimal Solution Structure

- When the uplink powers $\{p_\ell^{\mathrm{U}}\}$ are fixed, optimal receive beamforming are

$$\boldsymbol{v}_\ell = \frac{\tilde{\boldsymbol{v}}_\ell}{\|\tilde{\boldsymbol{v}}_\ell\|}, \ \tilde{\boldsymbol{v}}_\ell = \left(\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{g}_j \boldsymbol{g}_j^H + \sigma_z^2 \boldsymbol{I}_{N_t} \right)^{-1} \boldsymbol{g}_\ell,$$

- The optimal power solution is unique and satisfies

$$p_\ell^{\mathrm{U}} = \frac{\rho_\ell^{\mathrm{U}}}{\boldsymbol{g}_\ell^H \left(\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{g}_j \boldsymbol{g}_j^H + \sigma_z^2 \boldsymbol{I}_{N_t} \right)^{-1} \boldsymbol{g}_\ell}, \ \forall \ell \in \mathcal{L}.$$

- Fixed-point iterations converges to the optimal power values.

[SCR'07] B. Song, R. L. Cruz, and B. D. Rao, “Network duality for multiuser MIMO beamforming networks and applications,” IEEE Trans. Commun., vol. 55, no. 3, pp. 618–631, March 2007

Equivalent as an SDP

- Semidefinite Programming (SDP) reformulation

$$\max_{\{p_\ell^{\mathrm{U}}\geq 0\}} \quad \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}$$

$$\text{s.t.} \quad \sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{g}_j \boldsymbol{g}_j^H + \sigma_z^2 \boldsymbol{I}_{N_t} \succeq \left(\frac{p_\ell^{\mathrm{U}}}{\rho_\ell^{\mathrm{U}}}\right) \boldsymbol{g}_\ell \boldsymbol{g}_\ell^H, \ \forall \ell \in \mathcal{L},$$

where $\dfrac{1}{\rho_\ell^{\mathrm{U}}} \triangleq 1 + 1/\gamma_\ell^{\mathrm{U}}$.

- Thus, (HUL) is polynomial-time solvable.

[LHD'13] Y.-F. Liu, M. Hong, and Y.-H. Dai, "Max-min fairness linear transceiver design problem for a multi-user SIMO interference channel is polynomial time solvable," IEEE Signal Process. Lett., vol. 20, no. 1, pp. 27–30, Jan. 2013.

Multi-User Downlink

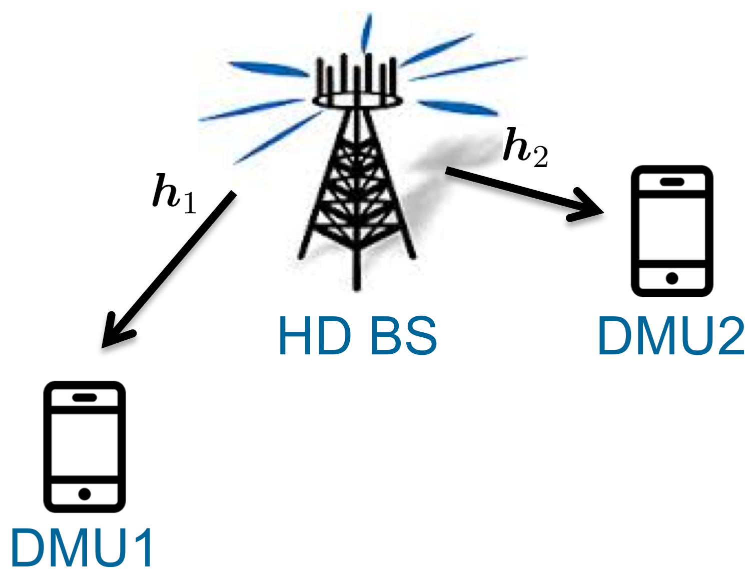
- Signal model

Transmit signal

$$\boldsymbol{x}(t) = \sum_{i=1}^{K} \boldsymbol{w}_i s_i^{\mathrm{D}}(t)$$

Transmit beamformer

$\boldsymbol{w}_1, \boldsymbol{w}_2$



Received signal at user i

$$y_i^{\mathrm{D}}(t) = \boldsymbol{h}_i^H \sum_{k=1}^{K} \boldsymbol{w}_k s_k^{\mathrm{D}}(t) + z_i^{\mathrm{D}}(t), \ \forall i \in \mathcal{K}$$

Signal-to-interference-plus-noise ratio (SINR)

$$\frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2}{\sum_{k \neq i}^{K} |\boldsymbol{h}_i^H \boldsymbol{w}_k|^2 + \sigma_i^2}, \quad i \in \mathcal{K}$$

Optimal Transmit Beamforming

- Design problem

$$\text{(HDL)} \qquad \min_{\{\boldsymbol{w}_k\}} \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2$$

$$\text{s.t.} \quad \frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2}{\sum_{k\neq i}^{K} |\boldsymbol{w}_k^H \boldsymbol{h}_i|^2 + \sigma_i^2} \geq \gamma_i^{\mathrm{D}}, \;\; I \in \mathcal{K}$$

where γ_i^{D} is the target SINR for user i .

- Non-convex, but is polynomial time solvable [GSSBO'10].

[GSSBO'10] A. B. Gershman, N. D. Sidiropoulos, S. Shahbazpanahi, M. Bengtsson, and B. Ottersten, "Convex optimization-based beamforming," IEEE Signal Process. Mag., pp. 62–75, May 2010.

Equivalent as an SOCP or SDP

- Second-order cone programming (SOCP) reformulation (via a proper phase rotation)

$$\min_{\{\boldsymbol{w}_k\}} \sum_{k=1}^{K} \|\boldsymbol{w}_k\|^2$$

$$\text{s.t.} \quad \frac{\boldsymbol{h}_i^H \boldsymbol{w}_i}{\sqrt{\rho_i^{\mathrm{D}}}} \geq \sqrt{\sum_{k=1}^{K} |\boldsymbol{h}_i \boldsymbol{w}_k|^2 + \sigma_i^2}, \ k \in \mathcal{K}$$

- Moreover, SDP relaxation is tight to (HDL)!

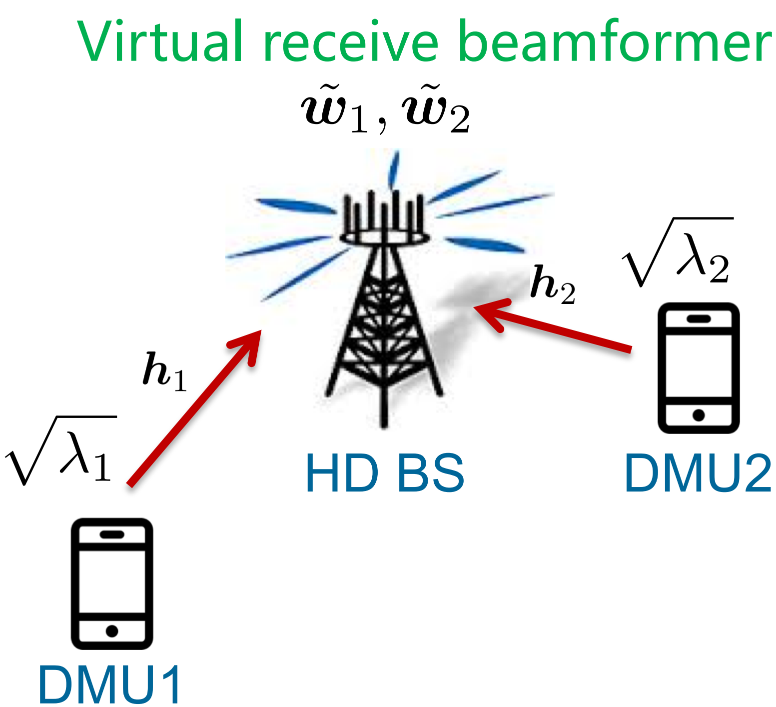
$$\boldsymbol{w}_i \boldsymbol{w}_i^H \Longleftrightarrow \boldsymbol{W}_i \succeq \mathbf{0}, \ \cancel{\mathrm{rank}(\boldsymbol{W}_i) = 1}$$

[BO'01] M. Bengtsson and B. Ottersten, "Optimal and suboptimal transmit beamforming," Chapter 18 in Handbook of Antennas in Wireless Communications, L. C. Godara, Ed., CRC Press, Aug. 2001.

[GSSBO'10] A. B. Gershman, N. D. Sidiropoulos, S. Shahbazpanahi, M. Bengtsson, and B. Ottersten, "Convex optimization-based beamforming," IEEE Signal Process. Mag., pp. 62–75, May 2010.

Uplink-Downlink Duality

- Via Lagrange duality, (HDL) has a virtual uplink problem

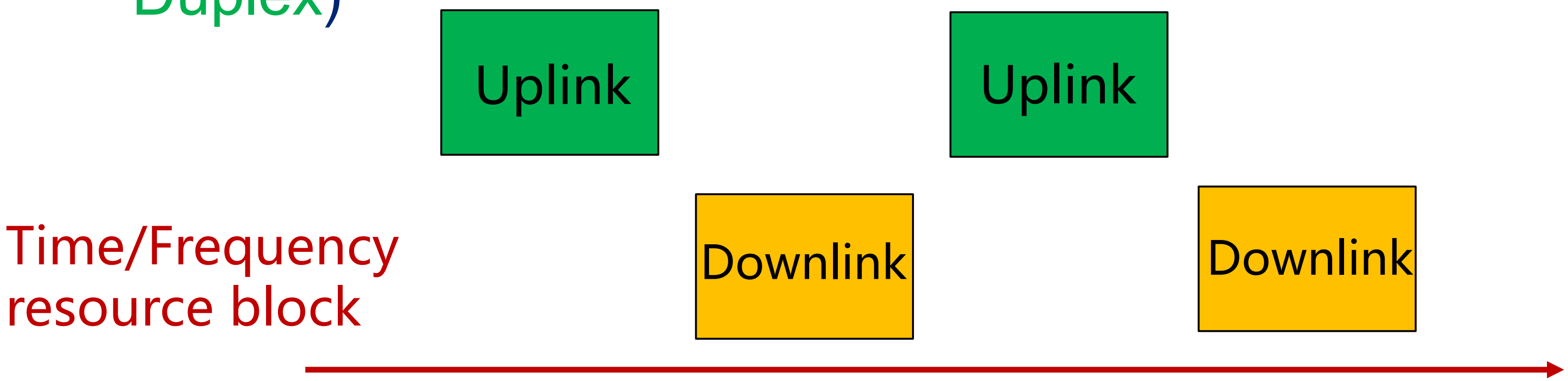


$$
\begin{aligned}
\min_{\{\tilde{\boldsymbol{w}}_i\},\{\lambda_i \geq 0\}} \quad & \sum_{i=1}^{K} \lambda_i \sigma_i^2 \\
\text{s.t.} \quad & \frac{\lambda_i |\tilde{\boldsymbol{w}}_i^H \boldsymbol{h}_i|^2 / \rho_i^{\mathrm{D}}}{\sum_{k=1}^{K} \lambda_k |\tilde{\boldsymbol{w}}_i^H \boldsymbol{h}_k|^2 + \|\tilde{\boldsymbol{w}}_i\|_2^2} \geq 1, \\
& i \in \mathcal{K}
\end{aligned}
$$

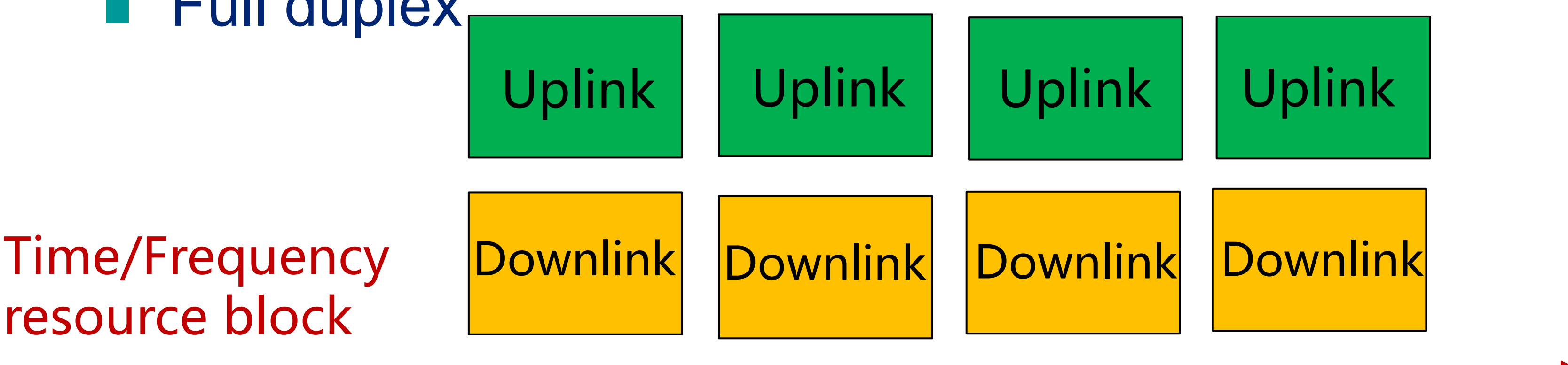
[GSSBO'10] A. B. Gershman, N. D. Sidiropoulos, S. Shahbazpanahi, M. Bengtsson, and B. Ottersten, "Convex optimization-based beamforming," IEEE Signal Process. Mag., pp. 62–75, May 2010.

Half Duplex vs Full Duplex

- Half duplex (Time Division Duplex/Frequency Division Duplex)

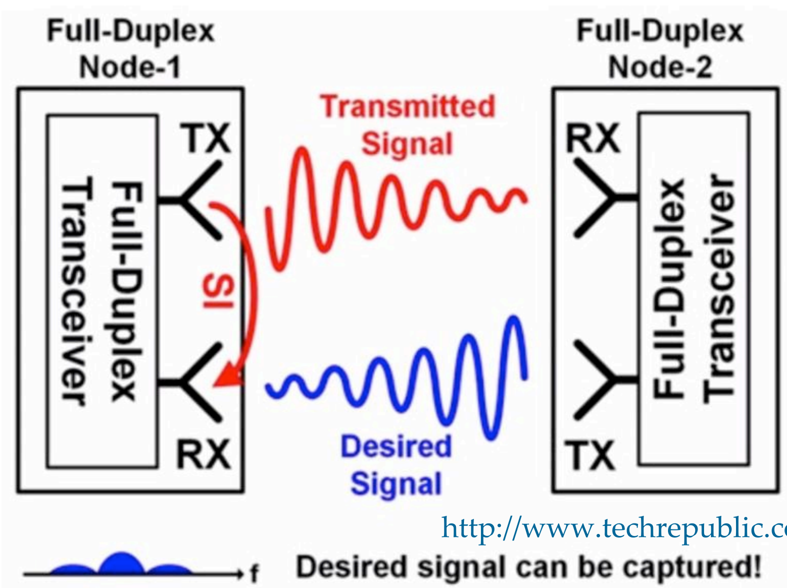


- Full duplex



Full-Duplex (FD) Communications

- Transmitting and receiving signals over the same spectrum and at the same time
- Ideally double the throughput comparing to TDD/FDD



http://www.techrepublic.com

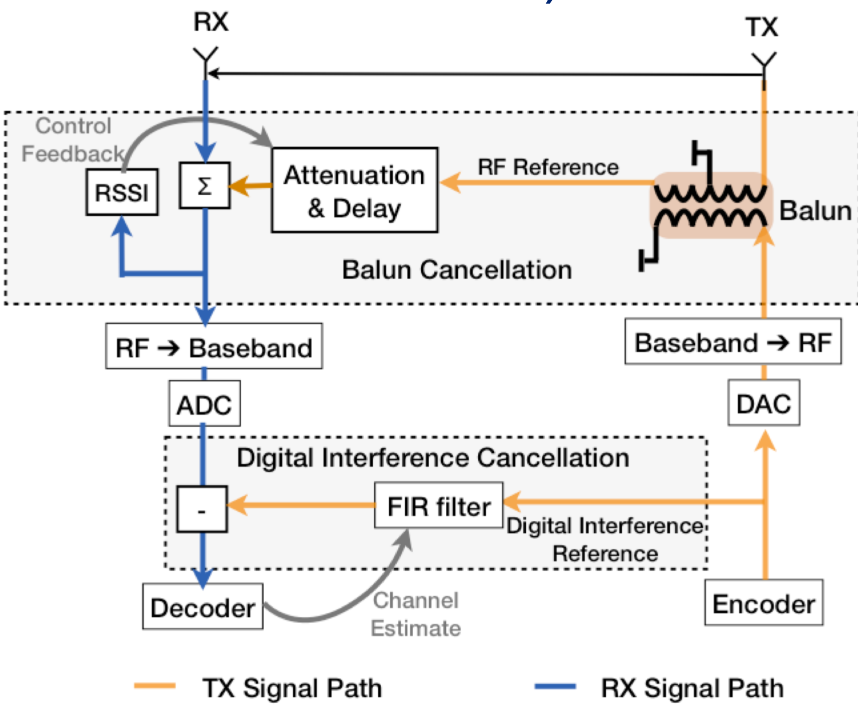
Challenge:

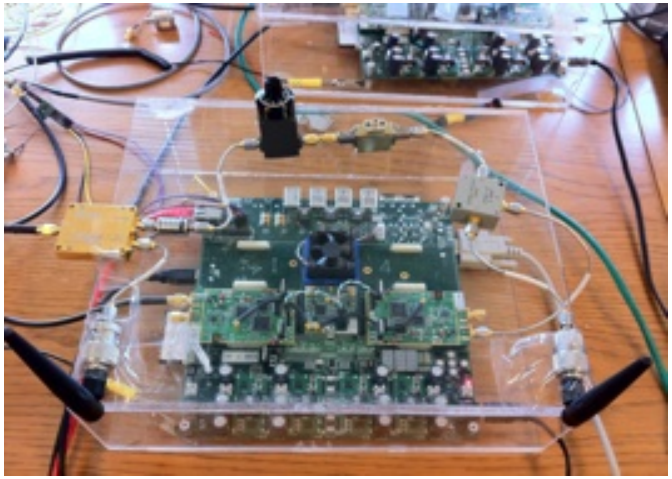
Self-interference (SI) can be 100dB larger than receiver noise and desired signal

A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities,"IEEE J. Sel. Areas Commun., vol. 32, no. 9, pp. 1637–1652, Sept. 2014.

Circuit Design

- FD technique has been successfully implemented (Kumi networks and S. Katti in Stanford; H. Krishnaswamy in Columbia Univ.)



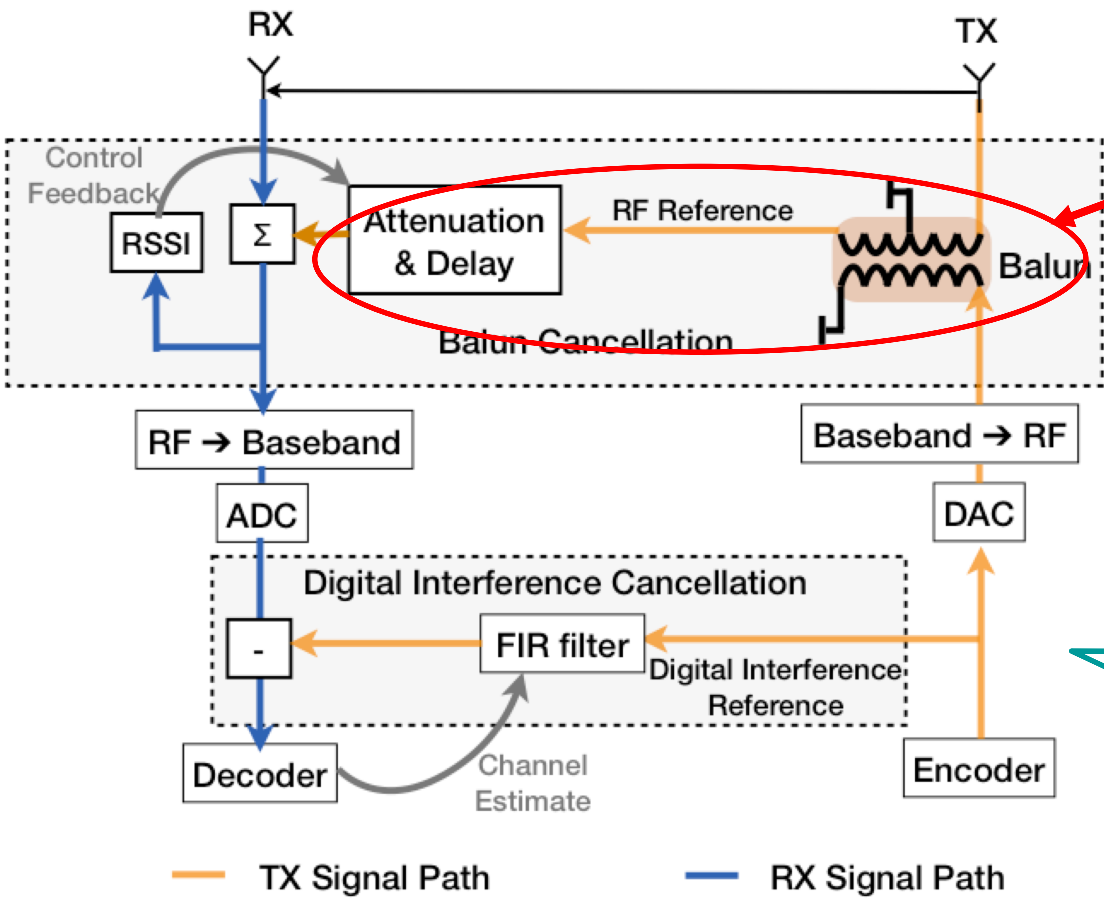


http://sing.stanford.edu/fullduplex/

D. Bharadia and S. Katti, “Full-duplex MIMO radios,” in Proc. USENIX NSDI, Seattle, 2014, pp. 359–372.

M. Duarte, A. Sabharwal, V. Aggarwal, R. Jana, K. K. Ramakrishnan, C. W. Rice, and N. K. Shankaranarayanan, “Design and characterization of a full-duplex multiantenna system for WiFi networks,” IEEE Trans. Veh. Technol., vol. 63, no. 3, pp. 1160–1177, Mar. 2014.

Circuit Design (cont')



Analog SI cancellation

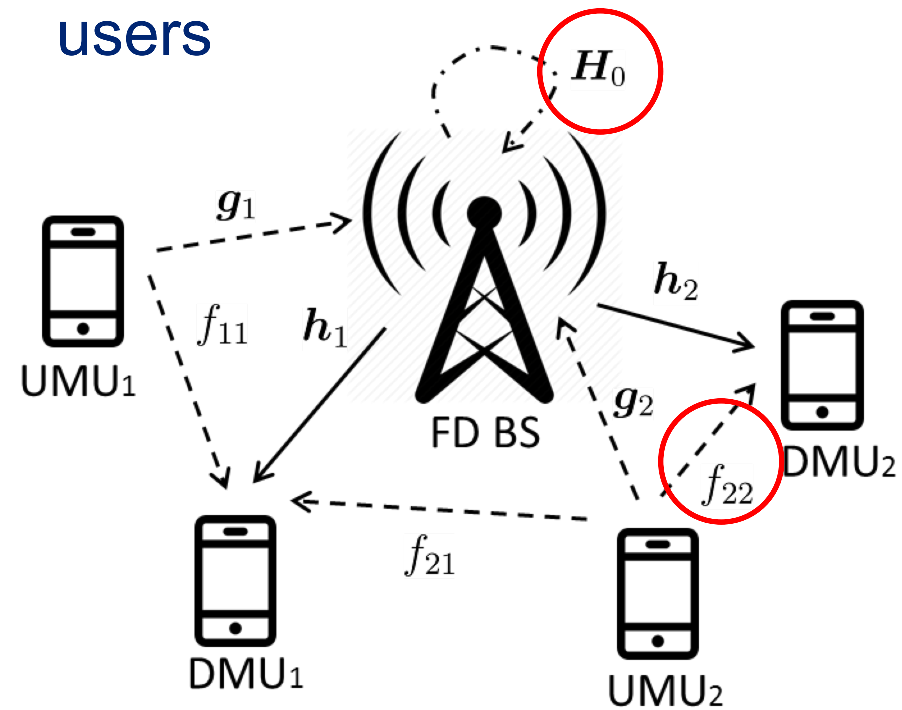
Limiting the SI to be within the dynamic ranges of ADC

Digital SI cancellation

D. Bharadia and S. Katti, "Full-duplex MIMO radios," in Proc. USENIX NSDI, Seattle, 2014, pp. 359–372.

FD Networking

- FD BS + HD mobile users
- Self-interference
- Co-channel interference from uplink users to downlink users



Challenge:
Joint design for uplink and downlink transmissions!

Y. Sun, D. W. K. Ng, J. Zhu, and R. Schober, "Multi-objective optimization for robust power efficient and secure full-duplex wireless communication systems," IEEE Trans. Wireless Commun., vol. 15, no. 8, pp. 5511–5526, Aug. 2016.
A. C. Cirik, O. Taghizadeh, R. Mathar, and T. Ratnarajah, "QoS considerations for full duplex multiuser MIMO systems," IEEE Trans. Commun., vol. 5, no. 1, pp. 36–39, Feb. 2016

System Model (cont')

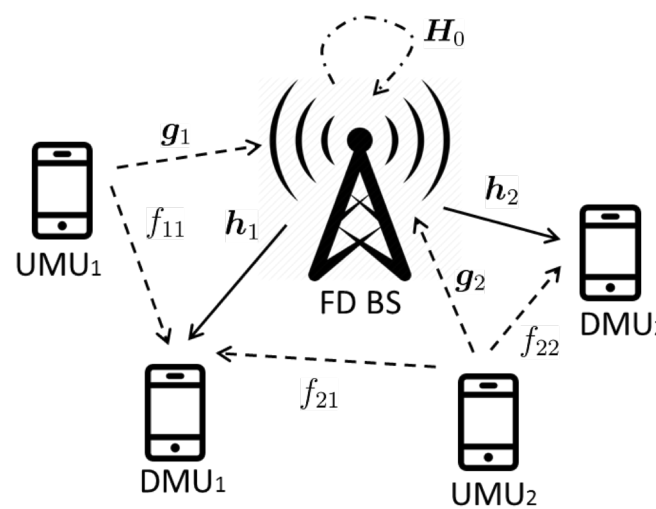
- Consider a network with K downlink mobile users (DMUs) and L uplink MUs (UMUs).

- Multiple-antenna BS and single-antenna MUs

- Received signal of the i th DMU:

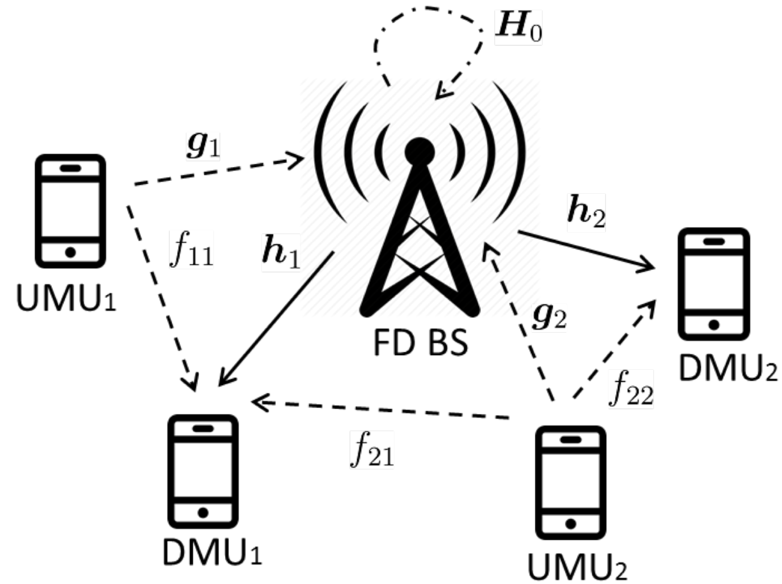
$$y_i^{\mathrm{D}}(t) = \boldsymbol{h}_i^H \left(\sum_{k=1}^{K} \boldsymbol{w}_k s_k^{\mathrm{D}}(t) + \boldsymbol{u}_{\mathrm{tx}}(t) \right)$$

$$+ \underbrace{\sum_{j=1}^{L} f_{ji} \sqrt{p_j^{\mathrm{U}}} s_j^{\mathrm{U}}(t)}_{\text{Uplink-to-downlink interference}} + z_i^{\mathrm{D}}(t), \ \forall i \in \mathcal{K},$$



System Model (cont')

- SINR of the i th DMU:



$$\mathrm{SINR}_i^{\mathrm{D}}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{U}}) \geq \gamma_i^{\mathrm{D}}$$

$$\Longleftrightarrow \frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2 / \rho_i^{\mathrm{D}}}{\sum_{k=1}^{K} \boldsymbol{w}_k^H \tilde{\boldsymbol{H}}_i \boldsymbol{w}_k + \underbrace{\sum_{j=1}^{L} p_j^{\mathrm{U}} |f_{ji}|^2}_{\text{Uplink-to-downlink interference}} + \sigma_i^2} \geq 1,$$

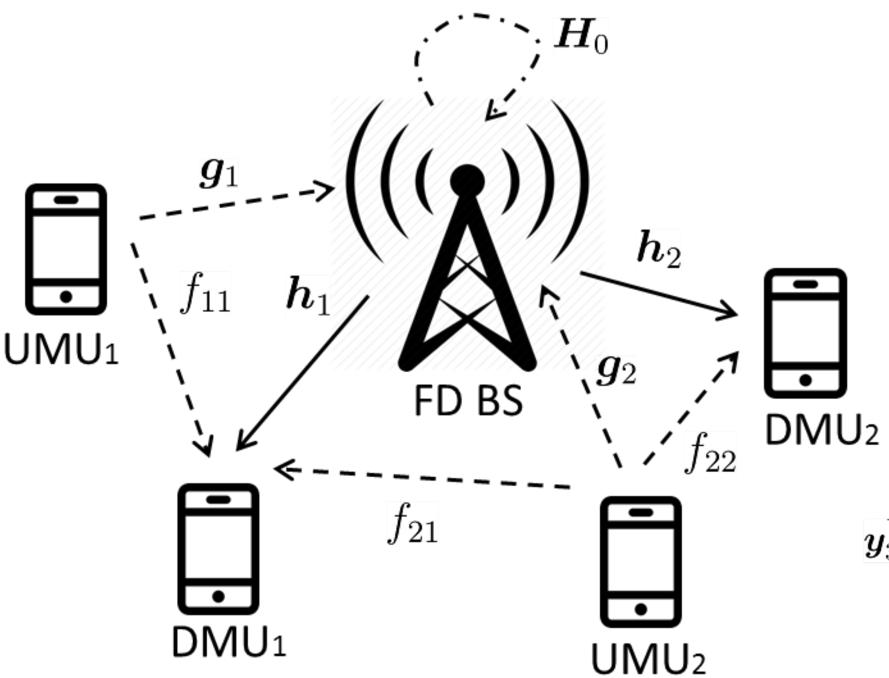
$$\tilde{\boldsymbol{H}}_i \triangleq \boldsymbol{h}_i \boldsymbol{h}_i^H + \beta_1 \mathrm{diag}(|\boldsymbol{h}_i|^2)$$

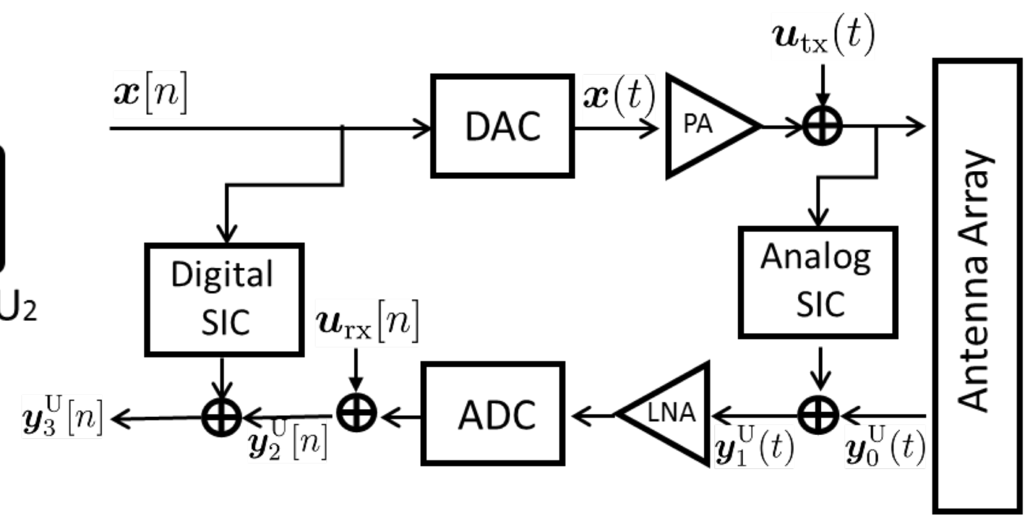
$$\frac{1}{\rho_i^{\mathrm{D}}} \triangleq 1 + 1/\gamma_i^{\mathrm{D}}$$

System Model (cont')

- Received signal of the FD BS

$$\boldsymbol{y}_0^{\mathrm{U}}(t) = \sum_{\ell=1}^{L} \boldsymbol{g}_\ell \sqrt{p_\ell^{\mathrm{U}}} s_\ell^{\mathrm{U}}(t) + \underbrace{\boldsymbol{H}_0(\boldsymbol{x}(t) + \boldsymbol{u}_{\mathrm{tx}}(t))}_{\text{Self-interference}} + \boldsymbol{z}^{\mathrm{U}}(t)$$





System Model (cont')

- Assume $\boldsymbol{H}_0 = \hat{\boldsymbol{H}}_0 + \boldsymbol{\Phi}_0$ where $\hat{\boldsymbol{H}}_0$ and $\boldsymbol{\Phi}_0$ are channel estimate and estimation error, respectively.
- Analog SIC removes $\hat{\boldsymbol{H}}_0(\boldsymbol{x}(t) + \boldsymbol{u}_{\text{tx}}(t))$ from $\boldsymbol{y}_0^{\text{U}}(t)$.
- Digital SIC further scales down the linear interference component and non-linear interference component by δ_1 and δ_2, respectively.

Residual self-interference

$$\boldsymbol{y}_3^{\text{U}}[n] = \sum_{\ell=1}^{L} \boldsymbol{g}_\ell \sqrt{p_\ell^{\text{U}}} s_\ell^{\text{U}}[n] + \sqrt{\delta_1}\boldsymbol{\Phi}_0 \boldsymbol{x}[n] + \sqrt{\delta_2}(\boldsymbol{\Phi}_0 \boldsymbol{u}_{\text{tx}}[n] + \boldsymbol{u}_{\text{rx}}[n]) + \boldsymbol{z}^{\text{U}}[n].$$

System Model (cont')

$$\boldsymbol{R}_{\Phi_0} \triangleq \mathbb{E}[\mathrm{vec}(\boldsymbol{\Phi}_0)\mathrm{vec}^H(\boldsymbol{\Phi}_0)]$$

$$\tilde{\boldsymbol{G}}_j \triangleq \boldsymbol{g}_j\boldsymbol{g}_j^H + \delta_2\beta_2\mathrm{diag}(|\boldsymbol{g}_j|^2)$$

$$\tilde{\sigma}_z^2 \triangleq (1+\delta_2\beta_2)\sigma_z^2$$

- SINR of the ℓ th UMU:

$$\mathrm{SINR}_\ell^{\mathrm{U}}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{U}}, \boldsymbol{v}_\ell) \geq \gamma_\ell^{\mathrm{U}}$$

$$\Leftrightarrow \frac{p_\ell^{\mathrm{U}}|\boldsymbol{v}_\ell^H\boldsymbol{g}_\ell|^2/\rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}}\boldsymbol{v}_\ell^H\tilde{\boldsymbol{G}}_j\boldsymbol{v}_\ell + \boldsymbol{v}_\ell^H\boldsymbol{\Omega}(\boldsymbol{W}, \boldsymbol{R}_{\boldsymbol{\Phi}_0})\boldsymbol{v}_\ell + \tilde{\sigma}_z^2\|\boldsymbol{v}_\ell\|_2^2} \geq 1,$$

Residual
self-interference

where $\boldsymbol{\Omega}(\boldsymbol{W}, \boldsymbol{R}_{\boldsymbol{\Phi}_0})$ and $\boldsymbol{\Lambda}(\boldsymbol{v}_\ell, \boldsymbol{R}_{\boldsymbol{\Phi}_0})$ are quadratic functions of $\boldsymbol{W}$ and $\boldsymbol{v}_\ell$, respectively.

System Model (cont')

- SINR of the ℓ th UMU:

Residual self-interference

$$\mathrm{SINR}_\ell^{\mathrm{U}}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{U}}, \boldsymbol{v}_\ell) \geq \gamma_\ell^{\mathrm{U}}$$

$$\Leftrightarrow \frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2 / \rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \boldsymbol{v}_\ell^H \boldsymbol{\Omega}(\boldsymbol{W}, \boldsymbol{R}_{\boldsymbol{\Phi}_0}) \boldsymbol{v}_\ell + \tilde{\sigma}_z^2 \|\boldsymbol{v}_\ell\|_2^2} \geq 1,$$

$$\Leftrightarrow \frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2 / \rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \sum_{k=1}^{K} \boldsymbol{w}_k^H \boldsymbol{\Lambda}(\boldsymbol{v}_\ell, \boldsymbol{R}_{\boldsymbol{\Phi}_0}) \boldsymbol{w}_k + \tilde{\sigma}_z^2 \|\boldsymbol{v}_\ell\|_2^2} \geq 1$$

where $\boldsymbol{\Omega}(\boldsymbol{W}, \boldsymbol{R}_{\boldsymbol{\Phi}_0})$ and $\boldsymbol{\Lambda}(\boldsymbol{v}_\ell, \boldsymbol{R}_{\boldsymbol{\Phi}_0})$ are quadratic functions of $\boldsymbol{W}$ and $\boldsymbol{v}_\ell$, respectively.

Problem Formulation

- QoS constrained Power minimization design

$$\text{(P)} \quad \min_{\substack{\{\boldsymbol{w}_k\},\{\boldsymbol{v}_\ell\},\\ \{p_\ell^{\mathrm{U}}\geq 0\}}} \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2 + \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}$$

$$\text{s.t.} \quad \mathrm{SINR}_i^{\mathrm{D}}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{U}}) \geq \gamma_i^{\mathrm{D}}, \ i \in \mathcal{K},$$

$$\mathrm{SINR}_\ell^{\mathrm{U}}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{U}}, \boldsymbol{v}_\ell) \geq \gamma_\ell^{\mathrm{U}}, \ \ell \in \mathcal{L},$$

- Challenging to handle

✓ non-convex

✓ coupled uplink and downlink transmissions

✓ results for HD systems no longer applicable

Problem Formulation

- QoS constrained Power minimization design

$$
\text{(P)} \quad \min_{\substack{\{\boldsymbol{w}_k\},\{\boldsymbol{v}_\ell\},\\ \{p_\ell^{\mathrm{U}}\geq 0\}}} \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2 + \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}
$$

$$
\text{s.t.} \quad \frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2/\rho_i^{\mathrm{D}}}{\sum_{k=1}^{K} \boldsymbol{w}_k^H \tilde{\boldsymbol{H}}_i \boldsymbol{w}_k + \sum_{j=1}^{L} p_j^{\mathrm{U}} |f_{ji}|^2 + \sigma_i^2} \geq 1, \ i \in \mathcal{K},
$$

$$
\frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2/\rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \boldsymbol{v}_\ell^H \boldsymbol{\Omega}(\boldsymbol{W}, \boldsymbol{R}_{\boldsymbol{\Phi}_0}) \boldsymbol{v}_\ell + \tilde{\sigma}_z^2 \|\boldsymbol{v}_\ell\|_2^2} \geq 1, \ \ell \in \mathcal{L},
$$

- Challenging to handle
  - ✓ non-convex
  - ✓ coupled uplink and downlink transmissions
  - ✓ results for HD systems no longer applicable

Problem Formulation

- QoS constrained Power minimization design

$$
\text{(P)} \quad \min_{\substack{\{\boldsymbol{w}_k\},\{\boldsymbol{v}_\ell\},\\ \{p_\ell^{\mathrm{U}}\geq 0\}}} \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2 + \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}
$$

$$
\text{s.t.} \quad \frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2/\rho_i^{\mathrm{D}}}{\sum_{k=1}^{K} \boldsymbol{w}_k^H \tilde{\boldsymbol{H}}_i \boldsymbol{w}_k + \sum_{j=1}^{L} p_j^{\mathrm{U}} |f_{ji}|^2 + \sigma_i^2} \geq 1,\ i \in \mathcal{K},
$$

$$
\frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2/\rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \boldsymbol{v}_\ell^H \boldsymbol{\Omega}(\boldsymbol{W}, \boldsymbol{R}_{\boldsymbol{\Phi}_0}) \boldsymbol{v}_\ell + \tilde{\sigma}_z^2 \|\boldsymbol{v}_\ell\|_2^2} \geq 1,\ \ \ell \in \mathcal{L},
$$

- We will show
  - ✓ a polynomial-time solvable case
  - ✓ efficient low-complexity algorithm for the general case

A Globally Solvable Case

- Consider a worst-case SI scenario: As the CSI error correlation matrix

$$\boldsymbol{R}_{\Phi_0} \preceq \lambda_{\max}(\boldsymbol{R}_{\boldsymbol{\Phi}_0})\boldsymbol{I}_{N_t}$$

we can bound

$$\boldsymbol{\Omega}(\boldsymbol{W}, \boldsymbol{R}_{\boldsymbol{\Phi}_0}) \preceq \xi \sum_{i=1}^{K} \|\boldsymbol{w}_i\|_2^2 \boldsymbol{I}_{N_t}$$

where $\xi \triangleq (\delta_1 + \delta_2\beta_1 + \delta_2\beta_2(1+\beta_1))\lambda_{\max}(\boldsymbol{R}_{\boldsymbol{\Phi}_0})$

- Or assume that the CSI errors are independent and identically distributed (i.i.d.)

$$\boldsymbol{R}_{\Phi_0} = \sigma_{\Phi_0}^2 \boldsymbol{I}_{N_t^2}$$

A Globally Solvable Case (cont')

- For such case, (P) is given by

$$\hat{\sigma}_i^2(\boldsymbol{p}^{\mathrm{U}}) \triangleq \sum_{j=1}^{L} p_j^{\mathrm{U}} |f_{ji}|^2 + \sigma_i^2$$

$$(\mathrm{P1}) \quad \min_{\substack{\{\boldsymbol{w}_k\},\{\boldsymbol{v}_\ell\},\\ \{p_\ell^{\mathrm{U}}\ge 0\}}} \ \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2 + \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}$$

$$\text{s.t.} \quad \frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2/\rho_i^{\mathrm{D}}}{\sum_{k=1}^{K} \boldsymbol{w}_k^H \tilde{\boldsymbol{H}}_i \boldsymbol{w}_k + \hat{\sigma}_i^2(\boldsymbol{p}^{\mathrm{U}})} \ge 1, \ \ i \in \mathcal{K},$$

$$\frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2/\rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \underbrace{\xi \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2 \|\boldsymbol{v}_\ell\|_2^2}_{\text{Residual self-interference}} + \tilde{\sigma}_z^2 \|\boldsymbol{v}_\ell\|_2^2} \ge 1, \ \ \ell \in \mathcal{L}.$$

- Still not convex
- Turn out to be polynomial-time globally solvable

A UL-DL Decomposable Subproblem

- Consider a problem (P_η)

$$F(\eta) = \min_{\substack{\{\boldsymbol{w}_k\},\{\boldsymbol{v}_\ell\},\\ \{p_\ell^{\mathrm{U}}\geq 0\}}} \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2 + \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}$$

$$\text{s.t.} \quad \frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2/\rho_i^{\mathrm{D}}}{\sum_{k=1}^{K} \boldsymbol{w}_k^H \tilde{\boldsymbol{H}}_i \boldsymbol{w}_k + \hat{\sigma}_i^2(\boldsymbol{p}^{\mathrm{U}})} \geq 1, \ i \in \mathcal{K},$$

$$\frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2/\rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \xi\eta\|\boldsymbol{v}_\ell\|_2^2 + \tilde{\sigma}_z^2 \|\boldsymbol{v}_\ell\|_2^2} \geq 1, \ \ell \in \mathcal{L},$$

- Here η is a fixed parameter.

A UL-DL Decomposable Subproblem

- Key observation 1:

$$F(\eta) = \min_{\substack{\{\boldsymbol{w}_k\},\{\boldsymbol{v}_\ell\},\\ \{p_\ell^{\mathrm{U}} \geq 0\}}} \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2 + \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}$$

$$\text{s.t.} \quad \frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2/\rho_i^{\mathrm{D}}}{\sum_{k=1}^{K} \boldsymbol{w}_k^H \tilde{\boldsymbol{H}}_i \boldsymbol{w}_k + \hat{\sigma}_i^2(\boldsymbol{p}^{\mathrm{U}})} \geq 1, \; i \in \mathcal{K},$$

$$\boxed{\frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2/\rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \underline{\xi\eta\|\boldsymbol{v}_\ell\|_2^2} + \tilde{\sigma}_z^2 \|\boldsymbol{v}_\ell\|_2^2} \geq 1, \; \ell \in \mathcal{L},}$$

Equality must hold.
Unique solution determined!
according to the HD Uplink design

B. Song, R. L. Cruz, and B. D. Rao, “Network duality for multiuser MIMO beamforming networks and applications,” IEEE Trans. Commun., vol. 55, no. 3, pp. 618–631, March 2007.
Y.-F. Liu, M. Hong, and Y.-H. Dai, “Max-min fairness linear transceiver design problem for a multi-user SIMO interference channel is polynomial time solvable,” IEEE Signal Process. Lett., vol. 20, no. 1, pp. 27–30, Jan. 2013.

A UL-DL Decomposable Subproblem

- **Proposition 1:** Suppose that (P_η) is feasible. Then it can be globally solved by solving the two problems in order

$$\{\boldsymbol{v}_\ell(\eta), p_\ell^{\mathrm{U}}(\eta)\}_{\ell=1}^{L} = \arg \min_{\{\boldsymbol{v}_\ell\},\{p_\ell^{\mathrm{U}} \geq 0\}} \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}$$

$$\text{s.t.} \quad \frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2 / \rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + (\xi\eta + \tilde{\sigma}_z^2) \|\boldsymbol{v}_\ell\|_2^2} \geq 1, \ \ell \in \mathcal{L},$$

$$\{\boldsymbol{w}_k(\eta)\}_{k=1}^{K} = \arg \min_{\{\boldsymbol{w}_k\}} \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2$$

$$\text{s.t.} \quad \frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2 / \rho_i^{\mathrm{D}}}{\sum_{k=1}^{K} \boldsymbol{w}_k^H \tilde{\boldsymbol{H}}_i \boldsymbol{w}_k + \hat{\sigma}_i^2(\boldsymbol{p}^{\mathrm{U}}(\eta))} \geq 1, \ i \in \mathcal{K}.$$

A UL-DL Decomposable Subproblem

$$\{\boldsymbol{v}_\ell(\eta), p_\ell^{\mathrm{U}}(\eta)\}_{\ell=1}^{L} = \arg \min_{\{\boldsymbol{v}_\ell\},\{p_\ell^{\mathrm{U}}\geq 0\}} \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}$$

$$\text{s.t.} \quad \frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2 / \rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + (\xi\eta + \tilde{\sigma}_z^2)\|\boldsymbol{v}_\ell\|_2^2} \geq 1, \ \ell \in \mathcal{L},$$

HD uplink problem
Polynomial-time solvable

$$\{\boldsymbol{w}_k(\eta)\}_{k=1}^{K} = \arg\min_{\{\boldsymbol{w}_k\}} \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2$$

$$\text{s.t.} \quad \frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2 / \rho_i^{\mathrm{D}}}{\sum_{k=1}^{K} \boldsymbol{w}_k^H \tilde{\boldsymbol{H}}_i \boldsymbol{w}_k + \hat{\sigma}_i^2(\boldsymbol{p}^{\mathrm{U}}(\eta))} \geq 1, \ i \in \mathcal{K}.$$

HD downlink problem
Polynomial-time solvable

A. B. Gershman, N. D. Sidiropoulos, S. Shahbazpanahi, M. Bengtsson, and B. Ottersten, “Convex optimization-based beamforming,” IEEE Signal Process. Mag., pp. 62–75, May 2010.

Search of Optimal η

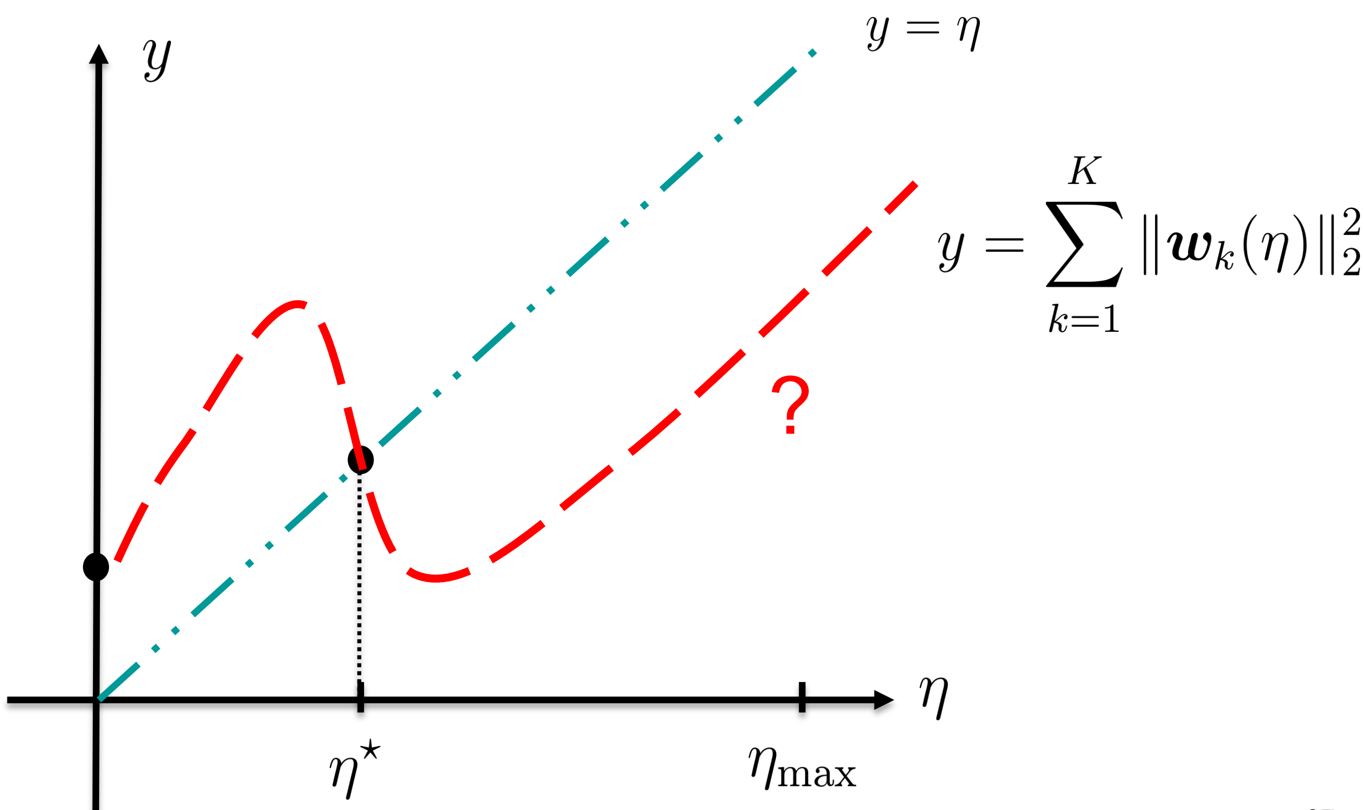
- Proposition 2: Suppose that (P1) is feasible.
  Let $\eta^\star \triangleq \sum_{k=1}^{K} \|\boldsymbol{w}_k^\star\|_2^2$. Then
  (1) $\eta^\star$ is unique;
  (2) when $\eta = \eta^\star$, $\{\boldsymbol{w}_k(\eta)\}$ of (P$_\eta$) is optimal to (P1)
  and satisfies $\sum_{k=1}^{K} \|\boldsymbol{w}_k(\eta)\|_2^2 = \eta^\star$

- Therefore, as long as $\eta^\star$ is obtained, then (P1) can be globally solved.

- How to get $\eta^\star$?

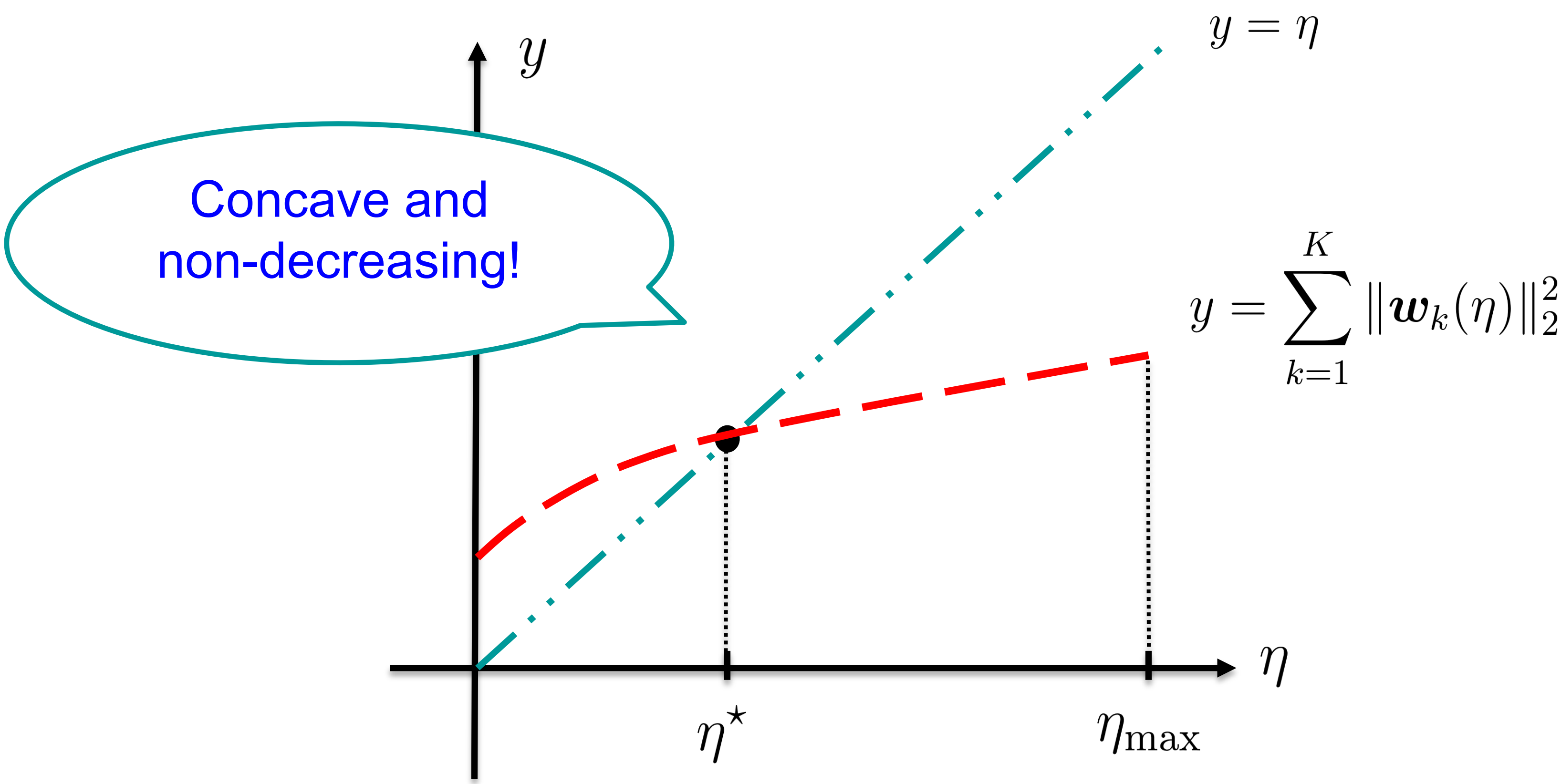
Search of Optimal η

- From Proposition 2, we know



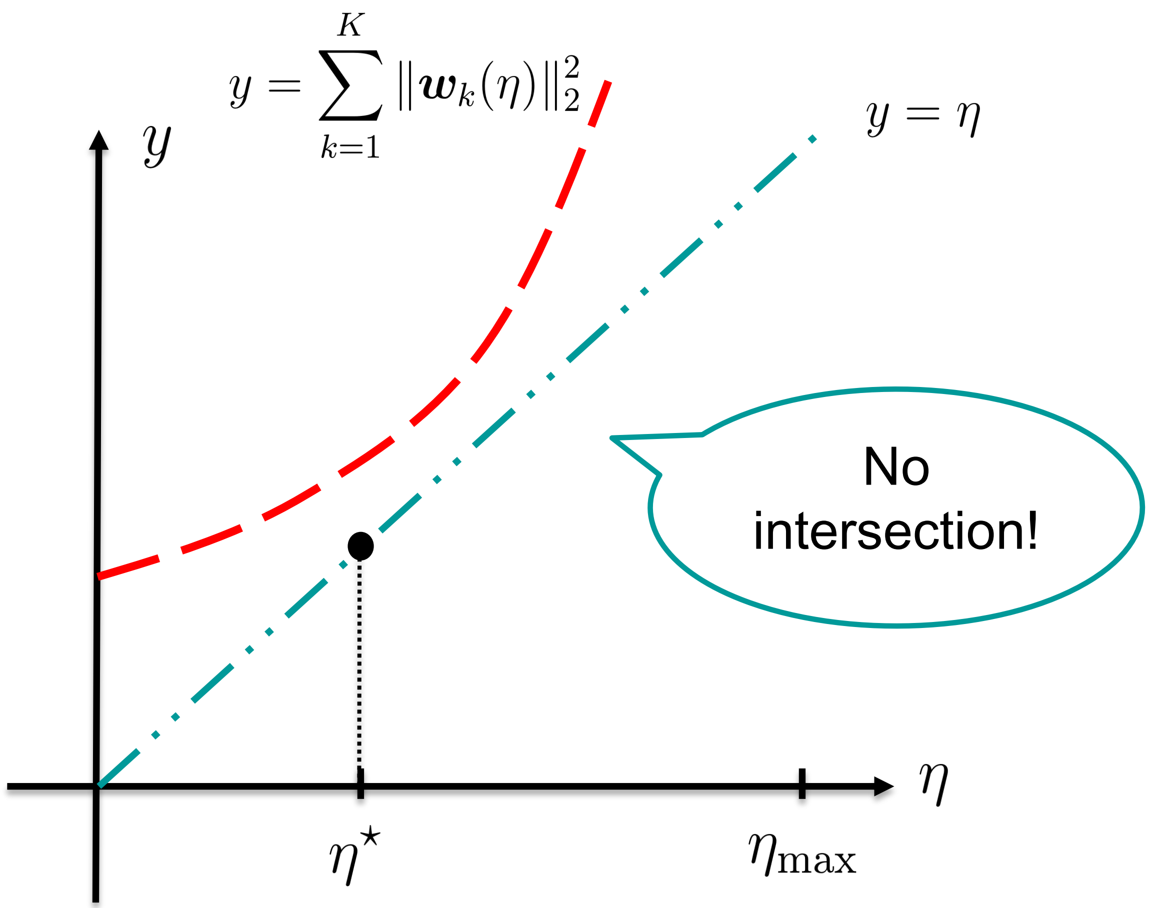
Search of Optimal η

- **Proposition 3:** Suppose that (P1) is feasible.



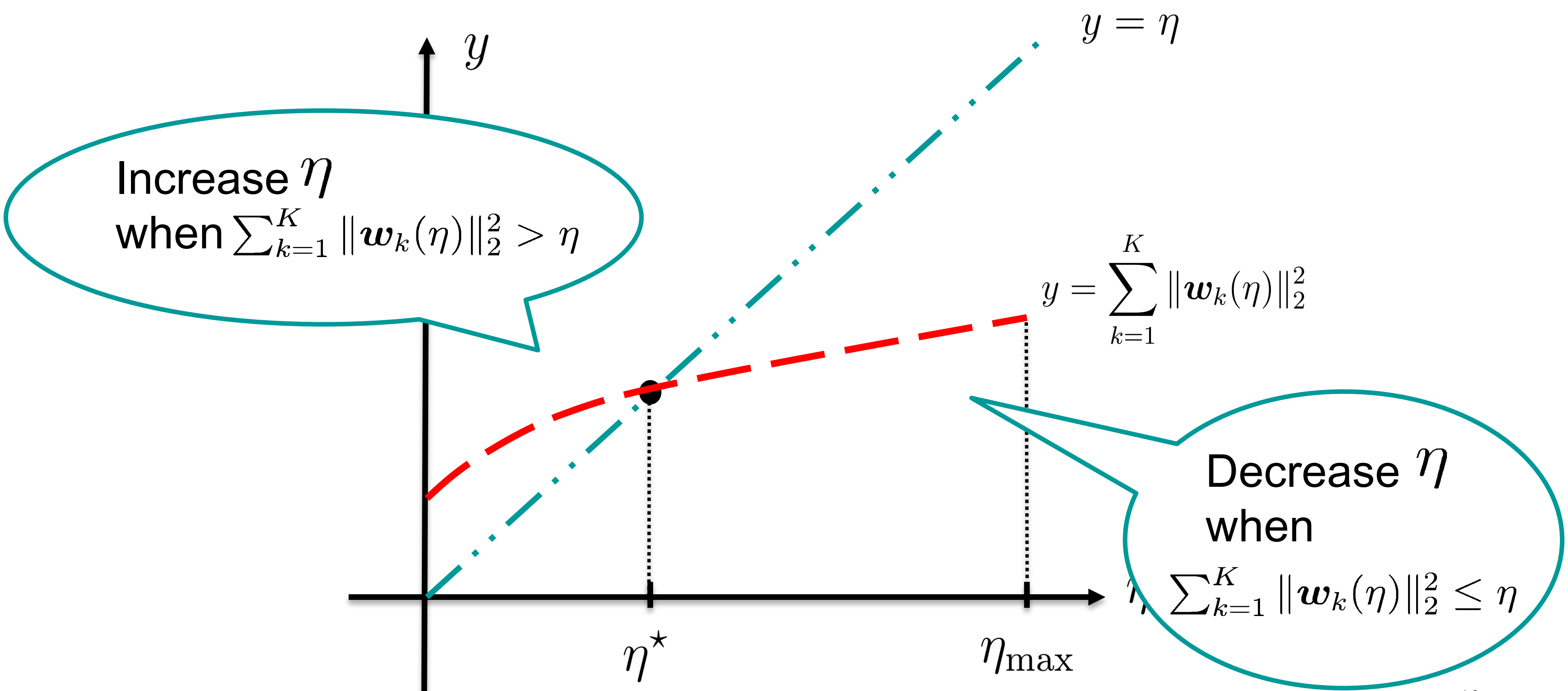
Search of Optimal η

- **Proposition 3:** (P1) is infeasible if and only if



Search of Optimal η

- Proposition 3 suggests a bisection search strategy



(P1) Is Polynomial-time Solvable

- Since bisection search of η is polynomial-time solvable, and (P_η) is polynomial-time solvable, we conclude:

  Theorem 1: Suppose that (P1) is feasible. Then (P1) is polynomial-time solvable.

- Insight: SI is the major bottleneck for the transceiver optimization of the FD networks.

  As long as the residual SI is negligible, the FD problem can be as easy as the HD problems

Alternating Optimization

- Recall our original problem (P)

$$
\text{(P)} \quad \min_{\substack{\{\boldsymbol{w}_k\},\{\boldsymbol{v}_\ell\},\\ \{p_\ell^{\mathrm{U}}\geq 0\}}} \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2 + \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}}
$$

$$
\begin{aligned}
\text{s.t.} \quad & \mathrm{SINR}_i^{\mathrm{D}}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{U}}) \geq \gamma_i^{\mathrm{D}}, \; i \in \mathcal{K}, \\
& \mathrm{SINR}_\ell^{\mathrm{U}}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{U}}, \boldsymbol{v}_\ell) \geq \gamma_\ell^{\mathrm{U}}, \; \ell \in \mathcal{L},
\end{aligned}
$$

- Analysis above implies that it is unlikely to globally solve (P) in a convex fashion.
- We employ an **AO method** to achieve a KKT solution of (P)

Alternating Optimization

- Suppose that UL beamformers $\{\boldsymbol{v}_\ell\}$ are fixed:

$$
\begin{aligned}
\min_{\{\boldsymbol{w}_k\},\{p_\ell^{\mathrm{U}}\geq 0\}} \quad & \sum_{k=1}^{K} \|\boldsymbol{w}_k\|_2^2 + \sum_{\ell=1}^{L} p_\ell^{\mathrm{U}} \\
\text{s.t.} \quad & \frac{|\boldsymbol{h}_i^H \boldsymbol{w}_i|^2/\rho_i^{\mathrm{D}}}{\sum_{k=1}^{K} \boldsymbol{w}_k^H \tilde{\boldsymbol{H}}_i \boldsymbol{w}_k + \sum_{j=1}^{L} p_j^{\mathrm{U}} |f_{ji}|^2 + \sigma_i^2} \geq 1, \ \forall i \in \mathcal{K}, \\
& \frac{p_\ell^{\mathrm{U}} |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2/\rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L} p_j^{\mathrm{U}} \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \underbrace{\sum_{k=1}^{K} \boldsymbol{w}_k^H \boldsymbol{\Lambda}(\boldsymbol{v}_\ell, \boldsymbol{R}_{\boldsymbol{\Phi}_0}) \boldsymbol{w}_k}_{\text{Residual self-interference}} + \tilde{\sigma}_z^2} \geq 1, \forall \ell \in \mathcal{L}.
\end{aligned}
$$

- Apply change of variables $q_\ell = \sqrt{p_\ell^{\mathrm{U}}},\ \ell \in \mathcal{L}$

Alternating Optimization

- Suppose that UL beamformers $\{\boldsymbol{v}_\ell\}$ are fixed:

$$\min_{\{\boldsymbol{w}_k\},\{q_\ell \geq 0\}} \quad \sum_{k=1}^{K} \|\boldsymbol{w}_k\|^2 + \sum_{\ell=1}^{L} q_\ell^2$$

$$\text{s.t.} \quad \frac{\boldsymbol{h}_i^H \boldsymbol{w}_i}{\sqrt{\rho_i^{\mathrm{D}}}} \geq \sqrt{\sum_{k=1}^{K} \|\tilde{\boldsymbol{H}}_i^{\frac{1}{2}} \boldsymbol{w}_k\|_2^2 + \sum_{j=1}^{L} q_j^2 |f_{ji}|^2 + \sigma_i^2}, \;\; k \in \mathcal{K},$$

$$\frac{q_\ell |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|}{\sqrt{\rho_\ell^{\mathrm{U}}}} \geq \sqrt{\sum_{j=1}^{L} q_j^2 \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \sum_{k=1}^{K} \|\boldsymbol{\Lambda}^{\frac{1}{2}}(\boldsymbol{v}_\ell, \boldsymbol{R}_{\boldsymbol{\Phi}_0}) \boldsymbol{w}_k\|_2^2 + \tilde{\sigma}_z^2}, \forall \ell \in \mathcal{L}.$$

- Apply change of variables $q_\ell = \sqrt{p_\ell^{\mathrm{U}}},\; \ell \in \mathcal{L}$
- Equivalent to a SOCP.

Alternating Optimization

- When $\{\boldsymbol{w}_k\}$ and $\{p_\ell^{\mathrm{U}}\}$ are fixed, $\{\boldsymbol{v}_\ell\}$ are updated by the maximum SINR solution

$$\boldsymbol{v}_\ell = \frac{\mathbf{M}_\ell^{-1}\boldsymbol{g}_\ell}{\|\mathbf{M}_\ell^{-1}\boldsymbol{g}_\ell\|_2}$$

where $\mathbf{M}_\ell \triangleq \sum_{j=1}^{L} p_j^{\mathrm{U}}\tilde{\boldsymbol{G}}_j + \boldsymbol{\Omega}(\boldsymbol{W}, \boldsymbol{R}_{\boldsymbol{\Phi}_0}) + \tilde{\sigma}_z^2\boldsymbol{I}_{N_t}.$

- Theorem 2: AO strategy yields a KKT solution of (P) as the iteration number goes to infinity.

Q. Shi, M. Razavayan, M. Hong, and Z.-Q. Luo, “SINR constrained beamforming for a MIMO multi-user downlink system,” IEEE Trans. Signal Process., vol. 64, no. 11, pp. 2920–2933, June 2016.

Extended Uplink-Downlink Duality

- Complexity of SOCP: $\log(1/\epsilon)\mathcal{O}(N_t^{3.5}K^{4.5})$ if $K=L$
- The classical UDD in HD systems can be extended to the FD system for solving (fixed $\{\boldsymbol{v}_\ell\}$)

$$\min_{\{\boldsymbol{w}_k\},\{p_\ell^{\mathrm{U}}\geq 0\}} \sum_{k=1}^{K}\|\boldsymbol{w}_k\|_2^2+\sum_{\ell=1}^{L}p_\ell^{\mathrm{U}}$$

$$\text{s.t.} \quad \frac{|\boldsymbol{h}_i^H\boldsymbol{w}_i|^2/\rho_i^{\mathrm{D}}}{\sum_{k=1}^{K}\boldsymbol{w}_k^H\tilde{\boldsymbol{H}}_i\boldsymbol{w}_k+\sum_{j=1}^{L}p_j^{\mathrm{U}}|f_{ji}|^2+\sigma_i^2}\geq 1,\ \forall i\in\mathcal{K},$$

$$\frac{p_\ell^{\mathrm{U}}|\boldsymbol{v}_\ell^H\boldsymbol{g}_\ell|^2/\rho_\ell^{\mathrm{U}}}{\sum_{j=1}^{L}p_j^{\mathrm{U}}\boldsymbol{v}_\ell^H\tilde{\boldsymbol{G}}_j\boldsymbol{v}_\ell+\sum_{k=1}^{K}\boldsymbol{w}_k^H\boldsymbol{\Lambda}(\boldsymbol{v}_\ell,\boldsymbol{R}_{\boldsymbol{\Phi}_0})\boldsymbol{w}_k+\tilde{\sigma}_z^2}\geq 1,\forall \ell\in\mathcal{L}.$$

F. Rashid-Farrokhi, K. J. R. Liu, and L. Tassiulas, “Transmit beamforming and power control for cellular wireless systems,” IEEE J. Sel. Areas Commun., vol. 16, no. 8, pp. 1437–1449, Oct. 1998.
M. Schubert and H. Boche, “Solution of the multiuser downlink beamforming problem with individual SINR constraints,” vol. 53, no. 1, pp. 18–28, Jan. 2004.

Extended Uplink-Downlink Duality

- Virtual problem:

$$(\{\tilde{\boldsymbol{w}}_k^\star\}, \boldsymbol{\lambda}^\star, \boldsymbol{\mu}^\star) = \arg \min_{\{\tilde{\boldsymbol{w}}_k\}, \boldsymbol{\lambda}, \boldsymbol{\mu} \succeq \mathbf{0}} \boldsymbol{\lambda}^T \boldsymbol{\sigma}^2 + \tilde{\sigma}_z^2 \boldsymbol{\mu}^T \mathbf{1}$$

$$\text{s.t.} \ \frac{\lambda_k |\tilde{\boldsymbol{w}}_k^H \boldsymbol{h}_k|^2 / \rho_k^{\mathrm{D}}}{\tilde{\boldsymbol{w}}_k^H (\sum_{i=1}^K \lambda_i \tilde{\boldsymbol{H}}_i + \sum_{\ell=1}^L \mu_\ell \boldsymbol{\Lambda}(\boldsymbol{v}_\ell, \boldsymbol{R}_{\boldsymbol{\Phi}_0}) + \boldsymbol{I}_{N_t}) \tilde{\boldsymbol{w}}_k} \geq 1, \ k \in \mathcal{K},$$

$$\frac{\mu_\ell |\boldsymbol{v}_\ell^H \boldsymbol{g}_\ell|^2 / \rho_\ell^{\mathrm{U}}}{\sum_{j=1}^L \mu_j \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \sum_{k=1}^K \lambda_k |f_{\ell k}|^2 + 1} \geq 1, \ell \in \mathcal{L},$$

F. Rashid-Farrokhi, K. J. R. Liu, and L. Tassiulas, “Transmit beamforming and power control for cellular wireless systems,” IEEE J. Sel. Areas Commun., vol. 16, no. 8, pp. 1437–1449, Oct. 1998.
M. Schubert and H. Boche, “Solution of the multiuser downlink beamforming problem with individual SINR constraints,” vol. 53, no. 1, pp. 18–28, Jan. 2004.

Extended Uplink-Downlink Duality

- Fixed-point equations:

$$\lambda_k = \mathcal{F}_k^{\mathrm{U}}(\boldsymbol{\lambda}, \boldsymbol{\mu}) \triangleq \frac{1}{\boldsymbol{h}_k^H \boldsymbol{Q}^{-1}(\boldsymbol{\lambda}, \boldsymbol{\mu}) \boldsymbol{h}_k / \rho_k^{\mathrm{D}}}, \ \forall k \in \mathcal{K},$$

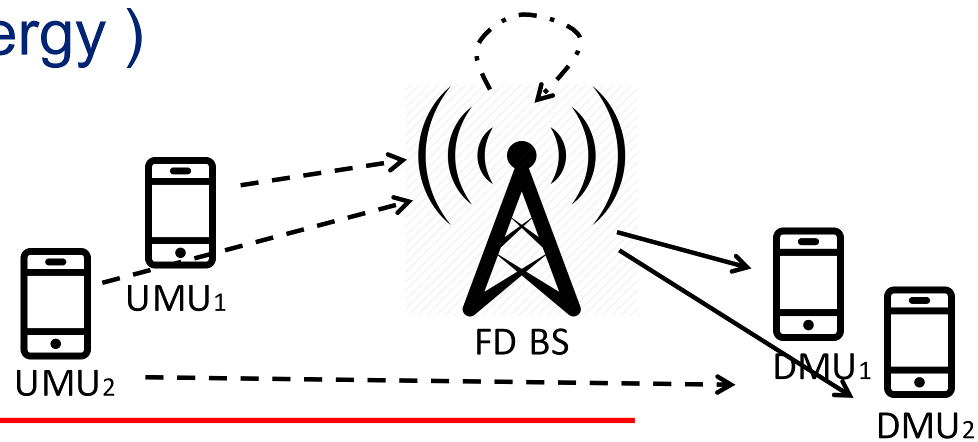
$$\mu_\ell = \mathcal{F}_\ell^{\mathrm{D}}(\boldsymbol{\lambda}, \boldsymbol{\mu}) \triangleq \frac{\sum_{j=1}^{L} \mu_j \boldsymbol{v}_\ell^H \tilde{\boldsymbol{G}}_j \boldsymbol{v}_\ell + \sum_{k=1}^{K} \lambda_k |f_{\ell k}|^2 + b_\ell}{|\tilde{\boldsymbol{v}}_\ell^H \boldsymbol{g}_\ell|^2 / \rho_\ell^{\mathrm{U}}}, \forall \ell \in \mathcal{L}.$$

- A fixed-point algorithm can be developed and efficiently implemented analogous to the HD system.
- Complexity: $\log(1/\epsilon)\mathcal{O}(N_t^3 + K^2)$ if $K = L$ and the FP iterations have a linear convergence rate

F. Rashid-Farrokhi, K. J. R. Liu, and L. Tassiulas, “Transmit beamforming and power control for cellular wireless systems,” IEEE J. Sel. Areas Commun., vol. 16, no. 8, pp. 1437–1449, Oct. 1998.
M. Schubert and H. Boche, “Solution of the multiuser downlink beamforming problem with individual SINR constraints,” vol. 53, no. 1, pp. 18–28, Jan. 2004.

Simulation Setting

- The BS has 10 antennas ($N_t = 10$)
- The path loss between the MUs and the BS is set to -80 dB and that between the UMUs and DMUs is set to -83 dB.
- The SI channel has a -10 dB path loss.
- Analog SIC uses LMMSE channel estimation ($E > 0$ denotes the training energy)

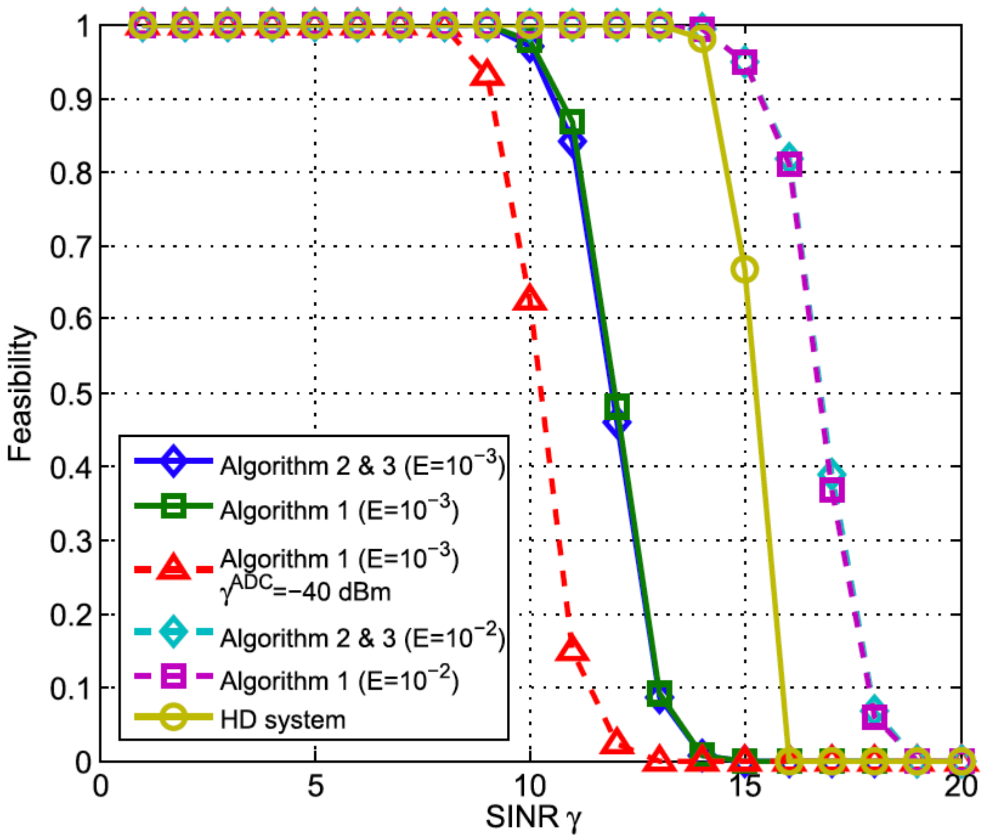


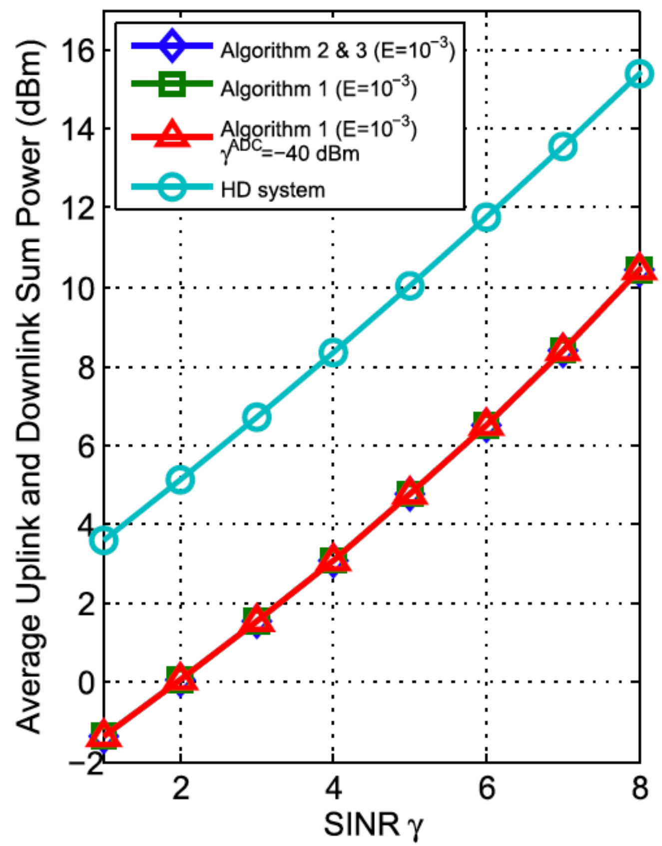
D. Bharadia, E. McMilin, and S. Katti, “Full duplex radios,” in Proc. ACM SIGCOMM, pp. 375–386, 2013.

E. Bjornson and B. Ottersten, “A framework for training-based estimation in arbitrarily correlated Rician MIMO channels with Rician disturbance,” IEEE Trans. Signal Process., vol. 58, no. 3, pp. 1807–1820, March 2010.

Simulation Results

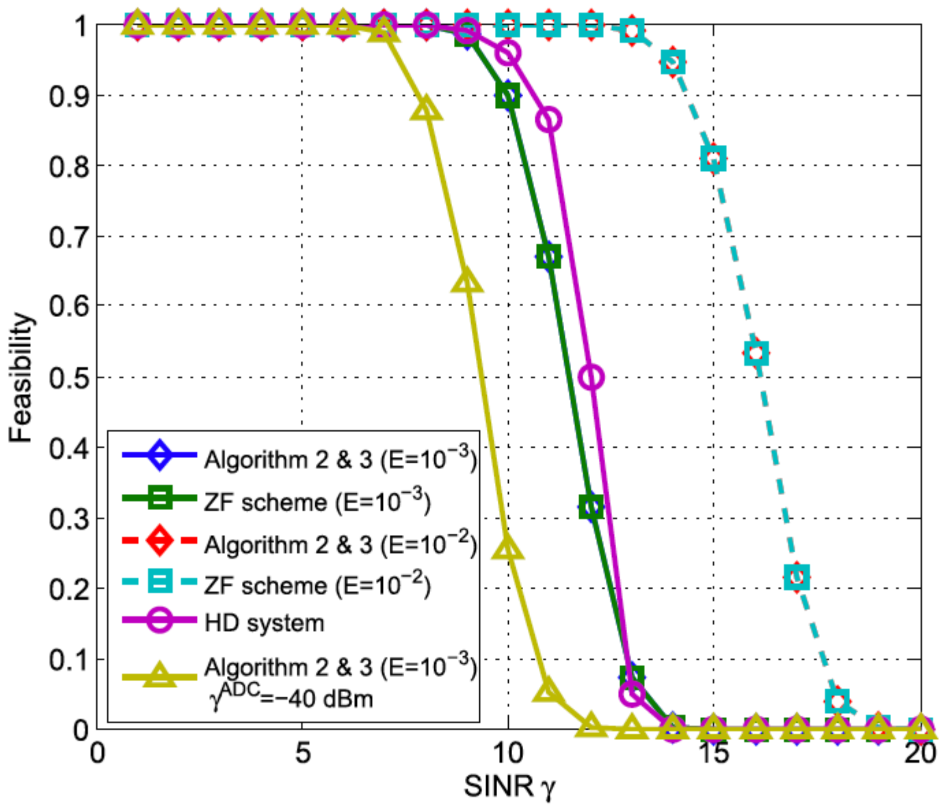
- (P1) $N_t = 10, K = L = 5$
- Bisection (Algorithm 1) vs AO method (Algorithm 2&3)

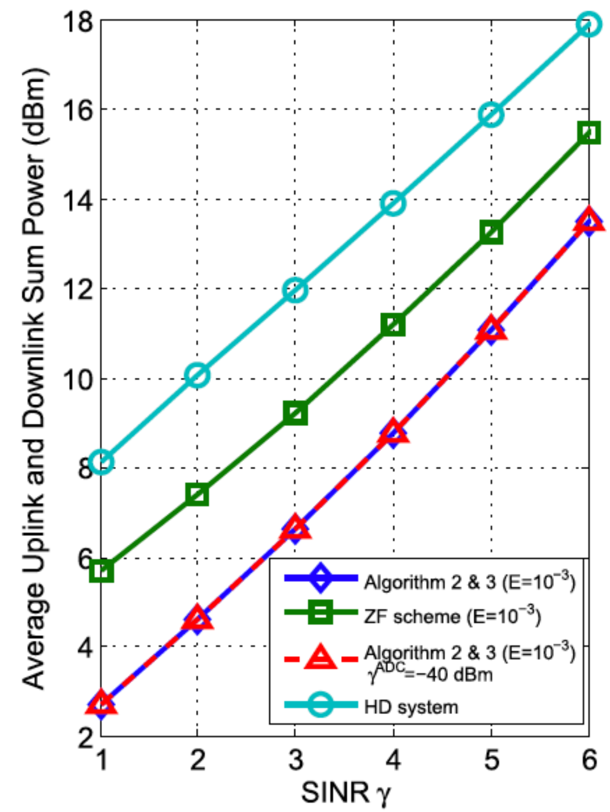




Simulation Results

- (P) $N_t = 10, K = L = 5$
- AO method (Algorithm 2&3) vs ZF scheme

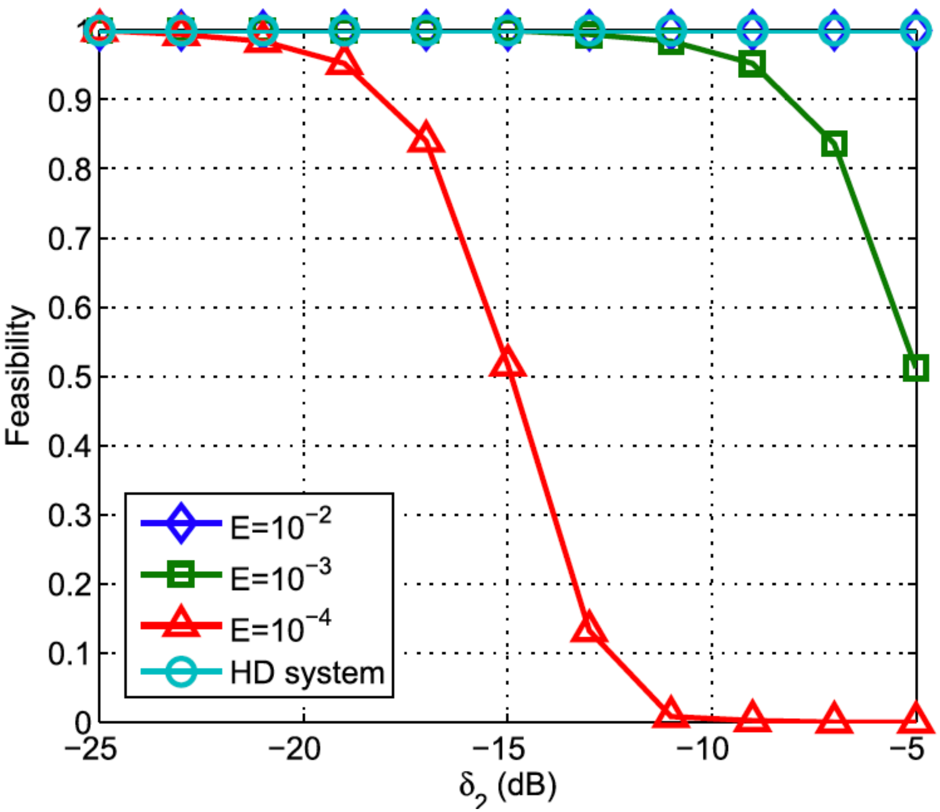


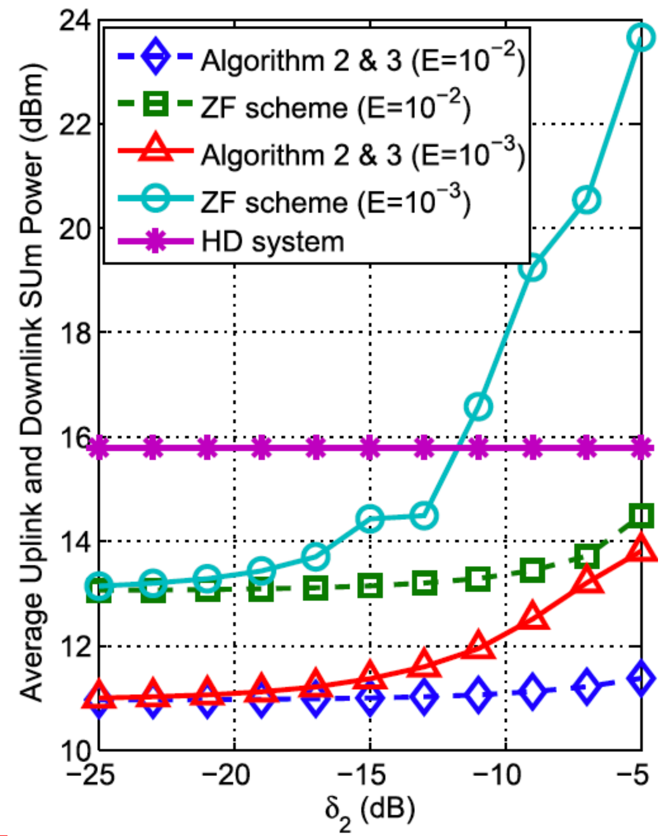


Y. Sun, D. W. K. Ng, J. Zhu, and R. Schober, "Multi-objective optimization for robust power efficient and secure full-duplex wireless communication systems," IEEE Trans. Wireless Commun., vol. 15, no. 8, pp. 5511–5526, Aug. 2016

Simulation Results

- (P) $N_t = 10, K = L = 8, \gamma = 5\text{dB}, \delta_1 = \delta_2 10^{-3}$
- AO method (Algorithm 2&3) vs ZF scheme





Y. Sun, D. W. K. Ng, J. Zhu, and R. Schober, "Multi-objective optimization for robust power efficient and secure full-duplex wireless communication systems," IEEE Trans. Wireless Commun., vol. 15, no. 8, pp. 5511–5526, Aug. 2016

Concluding Remarks

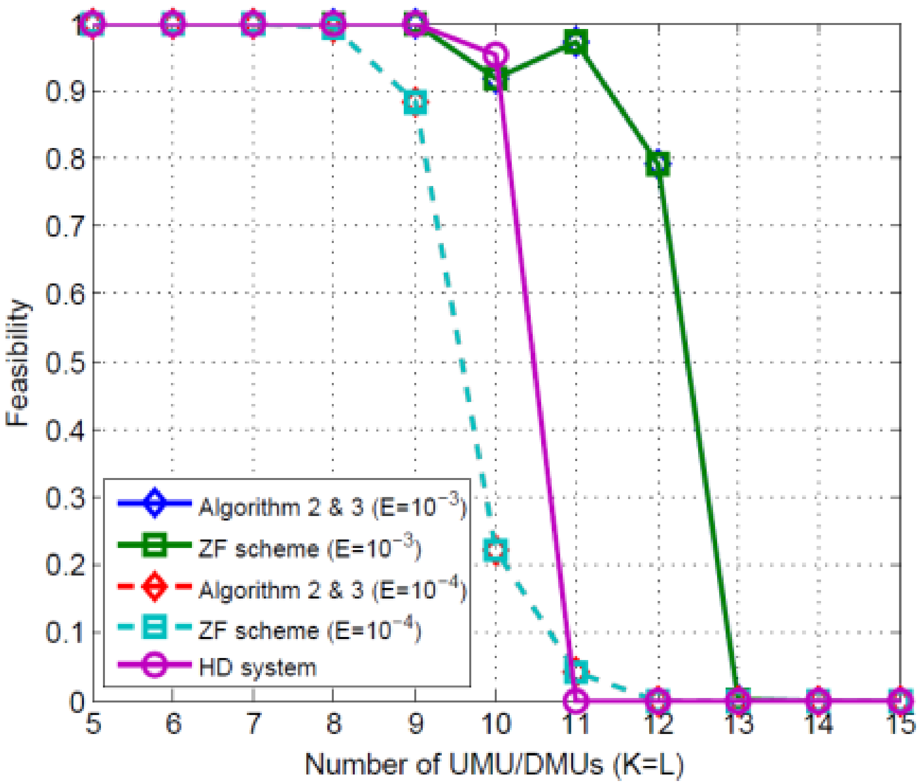
- The transceiver design for the FD network is challenging due to the SI and uplink-to-downlink co-channel interference.
- We have shown a special instance of (P) (i.e., (P1)) for which the global optimal solution can be obtained in polynomial time.
- An AO algorithm is also proposed for obtaining an efficient suboptimal solution.
- Both theoretical analysis for (P1) and numerical results indicate that the SI is the fundamental bottleneck of the FD system. Once SI can be sufficiently mitigated, the FD system greatly outperforms the HD system.

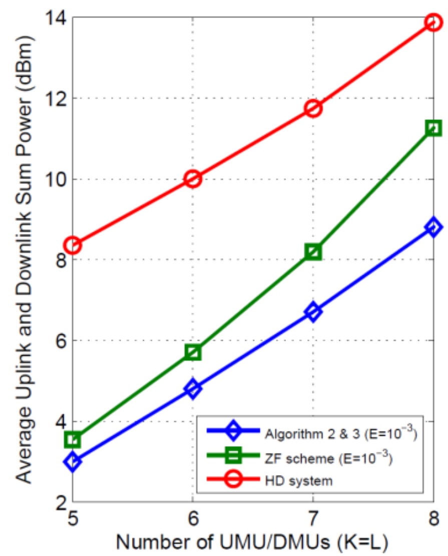

Thank You!!!
www.thebodytransformation.com


QUESTIONS?
COMMENTS?

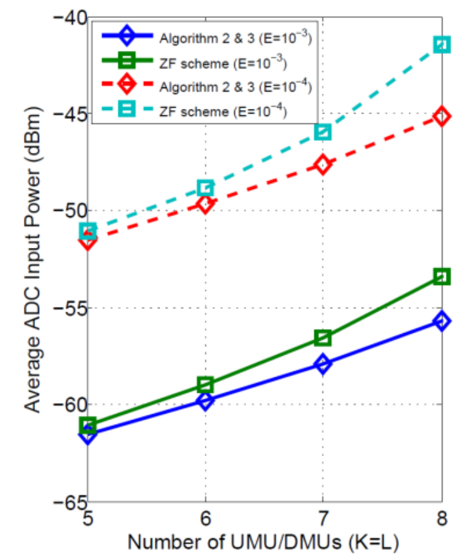
Simulation Results

- (P) $N_t = 10, \gamma = 5, K = L$
- AO method (Algorithm 2&3) vs ZF scheme





(b) Sum power

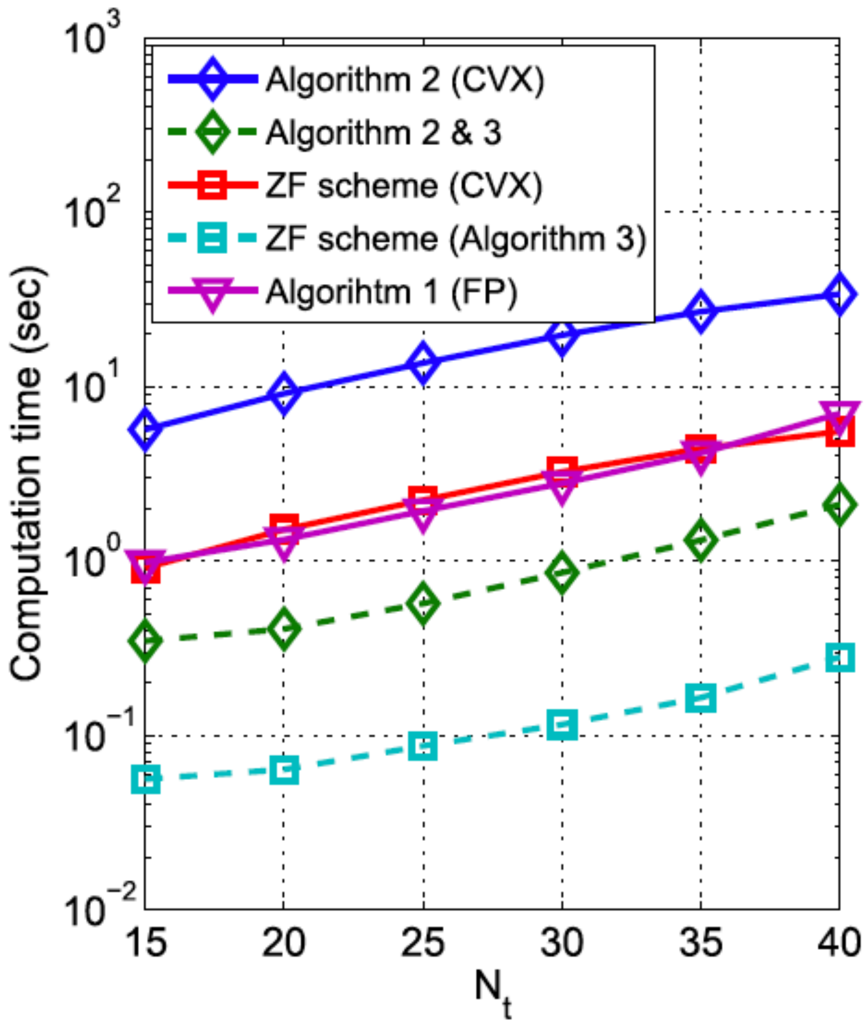


(c) ADC input signal power

Y. Sun, D. W. K. Ng, J. Zhu, and R. Schober, “Multi-objective optimization for robust power efficient and secure full-duplex wireless communication systems,” IEEE Trans. Wireless Commun., vol. 15, no. 8, pp. 5511–5526, Aug. 2016

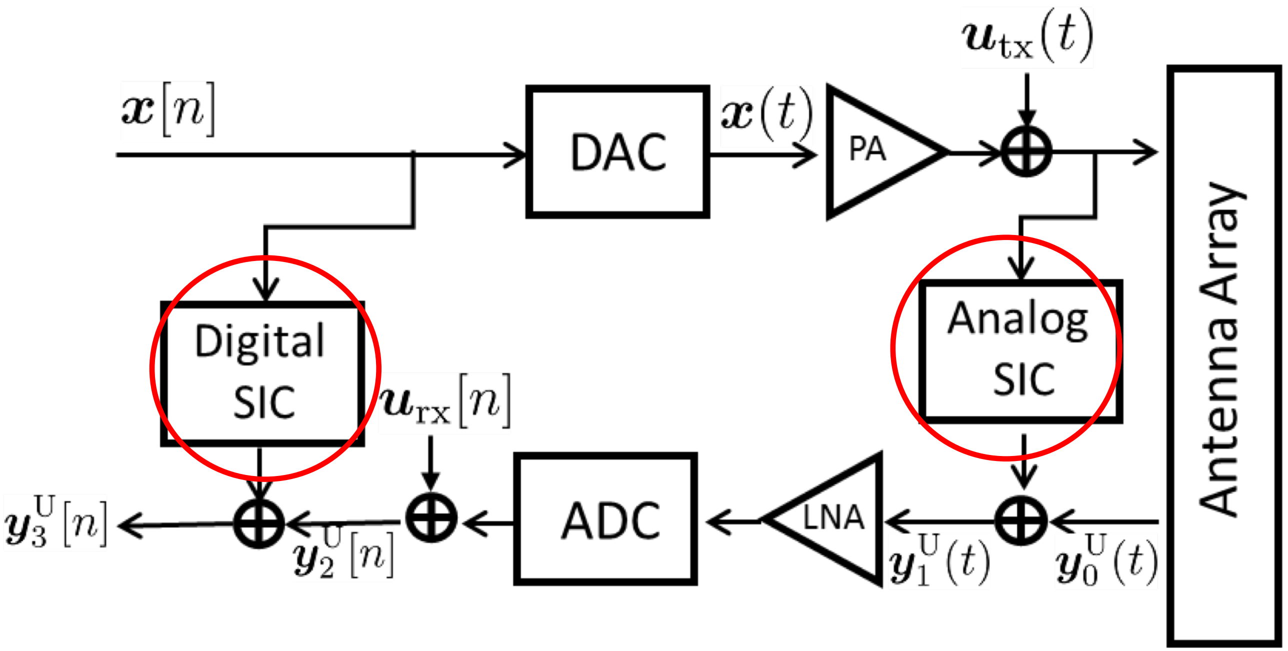
Simulation Results

- (P1) $N_t = 10, K = L = 5$
- Computation time



System Model

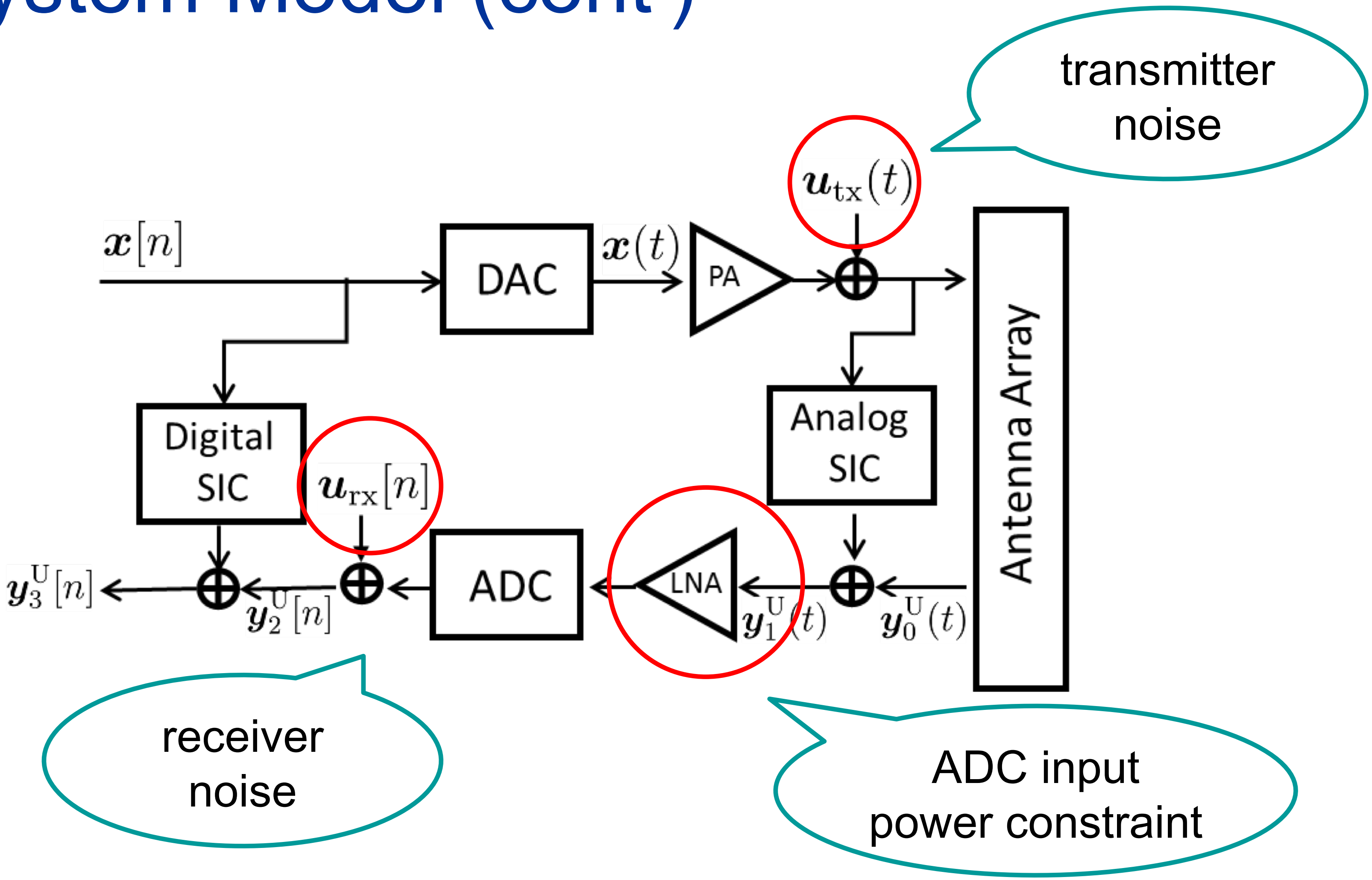
- Based on [Sabharwal'14], consider a block diagram of a FD BS



B. P. Day, A. R. Margetts, D. W. Bliss, and P. Schniter, "Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range," IEEE Trans. Signal Process., vol. 60, no. 7, pp. 3702–3713, July 2012.

D. Bharadia and S. Katti, "Full-duplex MIMO radios," in Proc. USENIX NSDI, Seattle, 2014, pp. 359–372.

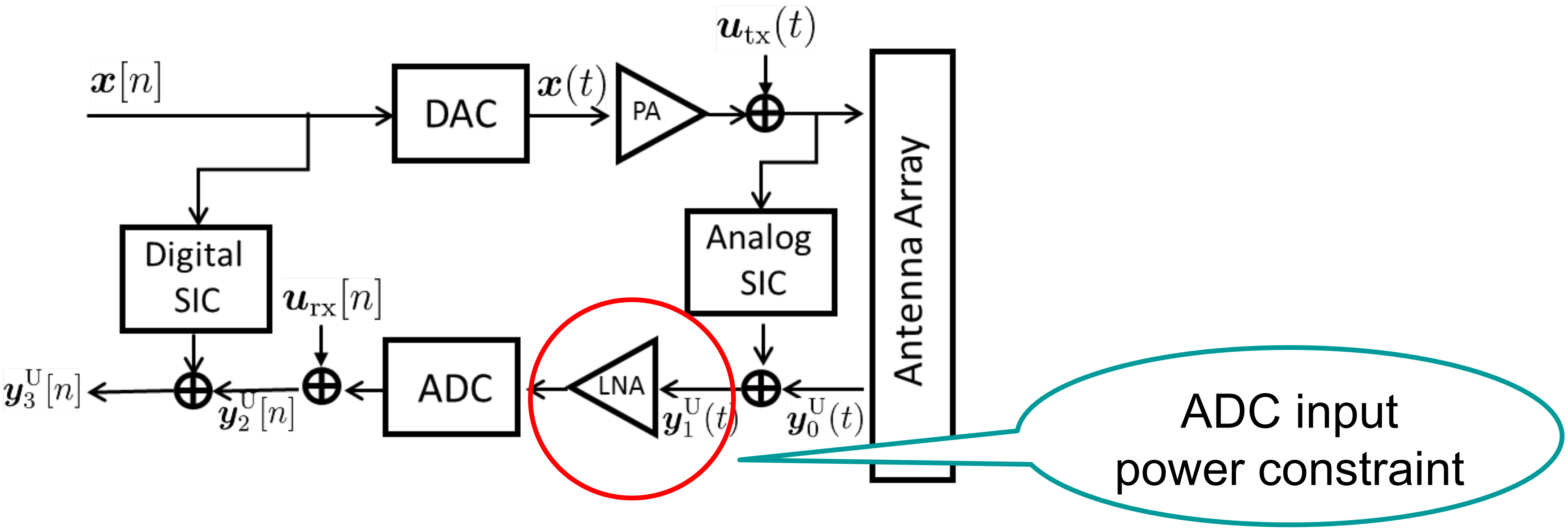
System Model (cont')



B. P. Day, A. R. Margetts, D. W. Bliss, and P. Schniter, "Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range," IEEE Trans. Signal Process., vol. 60, no. 7, pp. 3702–3713, July 2012.

D. Bharadia and S. Katti, "Full-duplex MIMO radios," in Proc. USENIX NSDI, Seattle, 2014, pp. 359–372.

System Model (cont')



- Constraint on ADC input signal power:

$$\sum_{k=1}^{K} \boldsymbol{w}_k^H \boldsymbol{\Upsilon}_n(\{\boldsymbol{R}_{\Phi_0,m}\})\boldsymbol{w}_k + \sum_{j=1}^{L} p_j^{\mathrm{U}} |\boldsymbol{e}_n^T \boldsymbol{g}_j|^2 + \sigma_z^2 \leq \gamma^{\mathrm{ADC}}$$

$$\forall n = 1, \ldots, N_t.$$

B. P. Day, A. R. Margetts, D. W. Bliss, and P. Schniter, “Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range,” IEEE Trans. Signal Process., vol. 60, no. 7, pp. 3702–3713, July 2012.

D. Bharadia and S. Katti, “Full-duplex MIMO radios,” in Proc. USENIX NSDI, Seattle, 2014, pp. 359–372.

Search of Optimal η

- Proved based on the solution structures of the HD uplink and downlink design problems