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PARALLEL BEAMFORMING DESIGN IN FULL DUPLEX SYSTEMS WITH PER-ANTENNA POWER CONSTRAINTS

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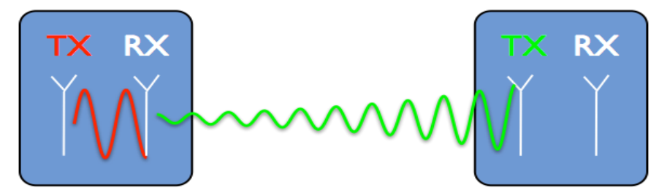
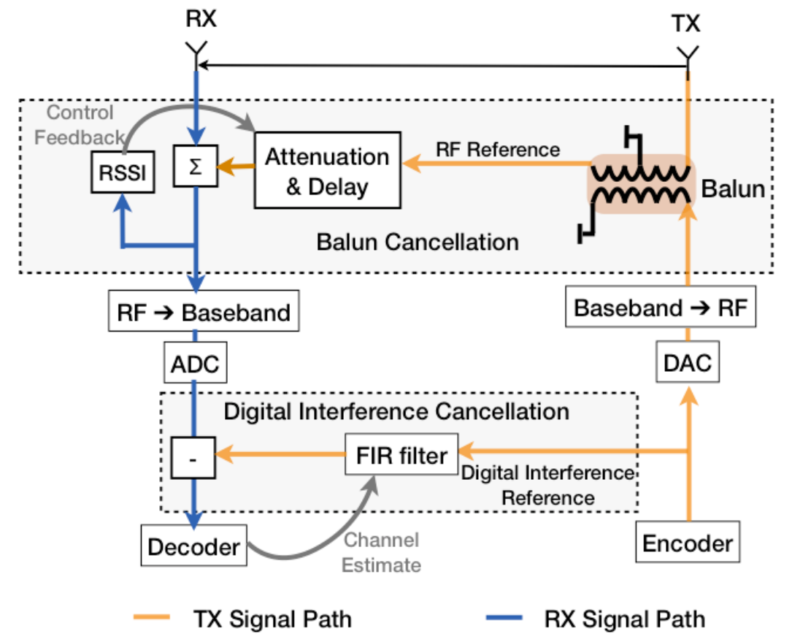
Introduction

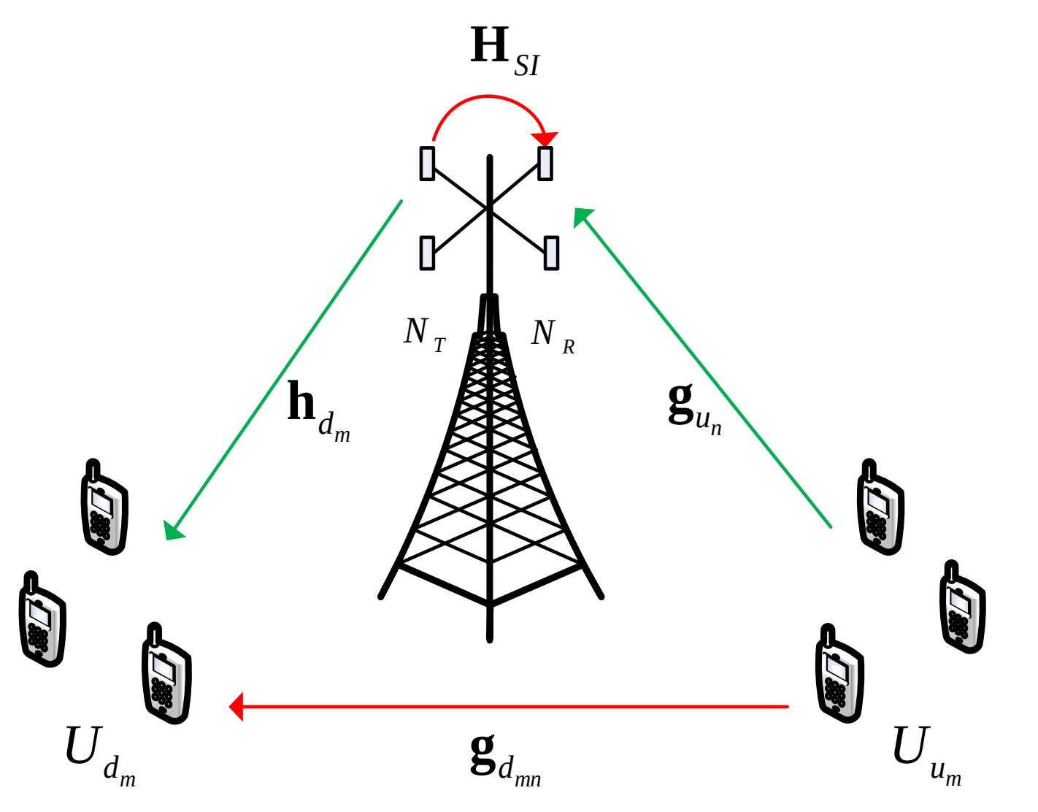


- ☐ Full duplex doubles the spectral efficiency
  - Simultaneous reception and transmission
  - **Strong** self-interference (SI)



- ☐ Suppress the SI to ground noise level
  - Antenna separation
  - Analog domain suppression
  - Digital domain suppression
- ☐ A majority of researched on FD
  - Power reduction, rate maximization
  - Second-order algorithms, centralized beamforming designs
  - high complexity especially when the number of antennas or uses becomes large
- ☐ Parallel low-complexity beamforming design for large-scale networks
  - The minimum weighted downlink SINR is maximized to achieve a better trade off between user requirement and fairness
  - Per-antenna power constraint is considered
  - Alternating direction method of multipliers (ADMM) is adopted

System model



System model in full duplex systems

- FD-BS simultaneously serves K_d downlink users and K_u uplink users
- FD-BS is equipped with $N = N_t + N_r$ antennas
- The transmitted downlink signal is
$$\boldsymbol{x}_d = \sum_{m=1}^{K_d} \boldsymbol{w}_{d_m} s_{d_m}$$
- The uplink signal sent by U_{d_m} is
$$x_{u_n} = \sqrt{p_{u_n}} s_{u_n}$$

Minimum weighted downlink SINR maximization Problem

- ☐ **Downlink transmission**

  The received SINR at m-th downlink user is

$$\gamma_{d_m} = \frac{\left|\mathbf{h}_{d_m}^H \mathbf{w}_{d_m}\right|^2}{\sum_{i=1,i\neq m}^{K_d}\left|\mathbf{h}_{d_m}^H \mathbf{w}_{d_i}\right|^2 + \sum_{n=1}^{K_u} p_{u_n}\left|g_{d_{mn}}\right|^2 + \sigma_{d_m}^2}.$$

- ☐ **Uplink transmission**

  The received SINR for n-th uplink user is

$$\gamma_{u_n} = \frac{p_{u_n}\left|\mathbf{w}_{u_n}^H \mathbf{g}_{u_n}\right|^2}{\sum_{m=1}^{K_d}\left|\mathbf{h}_{SI_n}\mathbf{w}_{d_m}\right|^2 + \sigma_u^2\left\|\mathbf{w}_{u_n}\right\|^2},$$

where $\mathbf{h}_{SI_n} = \mathbf{H}_{SI}^H \mathbf{w}_{u_n}$, $\mathbf{w}_{u_n}$ is the ZF receiver to cancel the inter-user interference

- ☐ **Problem formulation**

non-convex

$$\begin{aligned} &\max_{\{\mathbf{w}_{d_m}\}} \quad \min_{m=1,\ldots,K_d} \frac{\gamma_{d_m}}{\Gamma_{d_m}} && (5a)\\ &\text{s. t.} \quad \gamma_{u_n} \geq \Gamma_{u_n}, \forall n, && (5b)\\ &\sum_{m=1}^{K_d} \mathbf{w}_{d_m}^H \mathbf{R}_i \mathbf{w}_{d_m} \leq P_i^{BS}, i = 1, \ldots, N_t, && (5c)\end{aligned}$$

- Minimum weighted downlink SINR
- Uplink SINR constraint
- Downlink per-antenna power constraint

where Γ_{d_m} and Γ_{u_n} are desired SINRs of *m*-th downlink user and *n*-th uplink user, respectively; $\mathbf{R}_i \in \{0,1\}^{N_t \times N_t}$ is a zero matrix except that the *i*-th diagonal element is 1.

ADMM-based parallel beamforming design

- ☐ **Step 1: Problem reformulation**
  - Introduce an non-negative parameter, *t*, problem (5) is rewritten as

$$\begin{aligned} \mathcal{T}: \quad &\max_{\{\mathbf{w}_{d_m}\},t} \quad t && (6a)\\ &\text{s. t. } \gamma_{d_m} \geq t\Gamma_{d_m}, \forall m, \text{and (5b), (5c).} && (6b)\end{aligned}$$

  whose optimal value is $t^* = \mathcal{T}(\gamma, \mathrm{p})$, $\gamma = [\Gamma_{d_1}, \ldots, \Gamma_{d_{K_d}}]$ $\mathrm{p} = [P_1^{BS}, \ldots, P_{N_t}^{BS}]$

  - The QoS dual problem for this max-min fairness problem is

$$\begin{aligned} \mathcal{R}: \quad &\min_{\{\mathbf{w}_{d_m}\},r} \quad r && (7a)\\ &\text{s. t.} \quad \gamma_{d_m} \geq \Gamma_{d_m}, \forall m, \ \gamma_{u_n} \geq \Gamma_{u_n}, \forall n, && (7b)\\ &\frac{1}{P_i^{BS}} \sum_{m=1}^{K_d} \mathbf{w}_{d_m}^H \mathbf{R}_i \mathbf{w}_{d_m} \leq r, i = 1, \ldots, N_t, && (7c)\end{aligned}$$

Solve problem (7) instead

  whose optimal value is $r^* = \mathcal{R}(\gamma, \mathrm{p})$.

> **Proposition 1**
>
> With $N_t \geq K_u + K_d$, the relations between problem $\mathcal{T}$ and problem $\mathcal{R}$ are
> $1 = \mathcal{R}(\mathcal{T}(\gamma, \mathrm{p}) \cdot \gamma, \mathrm{p})$, and $t = \mathcal{T}(\gamma, \mathcal{R}(t \cdot \gamma, \mathrm{p}) \cdot \mathrm{p})$.

- ☐ **Step 2: Successive convex approximation (SCA)**
  - Problem (7) is solved iteratively and in each iteration, SCA is adopted.

in iteration *j+1,* the approximated problem is

$$\begin{aligned} &\min_{\{\mathbf{w}_{d_m}\},r} \quad r \quad \text{s. t.} && (10a)\\ &\Gamma_{d_m}\left(\sum_{i=1,i\neq m}^{K_d}\left|\mathbf{h}_{d_m}^H \mathbf{w}_{d_i}\right|^2 + \sum_{n=1}^{K_u} p_{u_n}\left|g_{d_{mn}}\right|^2 + \sigma_{d_m}^2\right)\\ &\leq 2\mathrm{Re}\{(\mathbf{w}_{d_m}^{(j)})^H \mathbf{h}_{d_m}\mathbf{h}_{d_m}^H \mathbf{w}_{d_m}\} - |\mathbf{h}_{d_m}^H \mathbf{w}_{d_m}^{(j)}|^2, \forall m, && (10b)\\ &\Gamma_{u_n}\left(\sum_{m=1}^{K_d}\left|\mathbf{h}_{SI_n}\mathbf{w}_{d_m}\right|^2 + \sigma_u^2\left\|\mathbf{w}_{u_n}\right\|^2\right)\\ &\qquad \leq p_{u_n}\left|\mathbf{w}_{u_n}^H \mathbf{g}_{u_n}\right|^2, \forall n, \text{ and (7c),} && (10c)\end{aligned}$$

Convex, but centralized design

- ☐ **Step 3: ADMM-based parallel beamforming design to solve problem (10)**
  - Decouple problem (10) by introducing local variables of coupled variables

$$a_{m,i} = \mathbf{h}_{d_m}^H \mathbf{w}_{d_i}, \forall m, i \in \{1, \ldots, K_d\}, \quad (11)$$
$$b_{n,m} = \mathbf{h}_{SI_n}^H \mathbf{w}_{d_m}, \forall n \in \{1, \ldots, K_u\}, \forall m \in \{1, \ldots, K_d\}, \quad (12)$$
$$\mathbf{v}_{d_m} = \mathbf{w}_{d_m}, \forall m \in \{1, \ldots, K_d\}, \alpha_i^d = r, \forall i \in \{1, \ldots, N_T\}. \quad (13)$$

  - Problem (10) can be rewritten as

$$\begin{aligned} &\min_{\mathbf{w}_d, r, \mathbf{a}, \mathbf{b}, \mathbf{v}_d, \boldsymbol{\alpha}^d} \quad r \quad \text{s. t.} && (14a)\\ &\Gamma_{d_m}\left(\sum_{i=1,i\neq m}^{K_d}\left|a_{m,i}\right|^2 + \sum_{n=1}^{K_u} p_{u_n}\left|g_{d_{mn}}\right|^2 + \sigma_{d_m}^2\right)\\ &\leq 2\mathrm{Re}\{(\mathbf{w}_{d_m}^{(j)})^H \mathbf{h}_{d_m} a_{m,m}\} - |\mathbf{h}_{d_m}^H \mathbf{w}_{d_m}^{(j)}|^2, \forall m, && (14b)\\ &\Gamma_{u_n}\left(\sum_{m=1}^{K_d}|b_{n,m}|^2 + \sigma_u^2\left\|\mathbf{w}_{u_n}\right\|^2\right) \leq p_{u_n}\left|\mathbf{w}_{u_n}^H \mathbf{g}_{u_n}\right|^2, \forall n, && (14c)\\ &\frac{1}{P_i^{BS}} \sum_{m=1}^{K_d} \mathbf{v}_{d_m}^H \mathbf{R}_i \mathbf{v}_{d_m} \leq \alpha_i^d, i = 1, \ldots, N_t, && (14d)\\ &(11) - (13), && (14e)\end{aligned}$$

⇒

problem (15) : consensus-form

$$\min_{\mathbf{w}_d, r, \mathbf{a}, \mathbf{b}, \mathbf{v}_d, \boldsymbol{\alpha}^d} r + g_{c_1}(\mathbf{a}) + g_{c_2}(\mathbf{b}) + g_{c_3}(\mathbf{v}_d, \boldsymbol{\alpha}^d)$$
$$\text{s. t. (14e)}$$

where g_{c_i} is a indicator function of the feasible region for *i*-th constraint c_i.

  - By applying ADMM, problem (15) can be solved alternatively.
  - Local variable set $\{\mathbf{a}, \mathbf{b}, \mathbf{v}_d, \boldsymbol{\alpha}^d\}$ can be updated in parallel

$$\min_{\mathbf{a}} \sum_{m=1}^{K_d}\sum_{i=1}^{K_d}\left|a_{m,i} - \mathbf{h}_{d_m}^H \mathbf{w}_{d_i} + \lambda_{m,i}^d\right|^2 \quad \text{s. t. (14b),} \quad (17)$$
$$\min_{\mathbf{b}} \sum_{m=1}^{K_d}\sum_{n=1}^{K_u}\left|b_{n,m} - \mathbf{h}_{SI_n}^H \mathbf{w}_{d_m} + \lambda_{m,n}^u\right|^2 \text{ s. t. (14c),} \quad (18)$$
$$\min_{\boldsymbol{\alpha}^d, \mathbf{v}_d} \sum_{i=1}^{N_T}\left|\alpha_i^d - r + \eta_i^d\right|^2 + \sum_{m=1}^{K_d}\left\|\mathbf{v}_{d_m} - \mathbf{w}_{d_m} + \mu_m\right\|^2 \text{s. t. (14d).} \quad (19)$$

  - Global variables $\{\mathbf{w}_d, r\}$ update can be decomposed into

$$\min_{\mathbf{w}_d} \sum_{m=1}^{K_d}\sum_{i=1}^{K_d}\left|a_{m,i} - \mathbf{h}_{d_m}^H \mathbf{w}_{d_i} + \lambda_{m,i}^d\right|^2 + \quad (22)$$
$$\sum_{m=1}^{K_d}\sum_{n=1}^{K_u}\left|b_{n,m} - \mathbf{h}_{SI_n}^H \mathbf{w}_{d_m} + \lambda_{m,n}^u\right|^2 + \sum_{m=1}^{K_d}\left\|\mathbf{v}_{d_m} - \mathbf{w}_{d_m} + \mu_m\right\|^2.$$
$$\min_r r + \frac{\rho}{2}\sum_{i=1}^{N_t}\left|\alpha_i^d - r + \eta_i^d\right|^2. \quad (23)$$

  - The dual variables $\{\boldsymbol{\lambda}^d, \boldsymbol{\lambda}^u, \boldsymbol{\mu}, \boldsymbol{\eta}^d\}$ update are

$$\lambda_{m,i}^d = \lambda_{m,i}^d + a_{m,i} - \mathbf{h}_{d_m}^H \mathbf{w}_{d_i}, \lambda_{n,m}^u = \lambda_{n,m}^u + b_{n,m} - \mathbf{h}_{SI_n}^H \mathbf{w}_{d_m}, \mu_m = \mu_m + \mathbf{v}_{d_m} - \mathbf{w}_{d_m}, \eta_i^d = \alpha_i^d - r + \eta_i^d;$$

SIMULATION RESULTS

- ☐ **Simulation setting**
  - Users are randomly distributed within a circle around FD-BS, radius is 250m.
  - For simplicity, we set $N_t = N_r$ and $K_d = K_u$.
  - $\mathbf{H}_{SI} \sim \mathcal{CN}(0, \sigma_{SI}^2)$, where $\sigma_{SI}^2 = -60$ dB represents for the SIC capability.
  - **SCA-ADMM**: The proposed ADMM-based parallel beamforming algorithm
  - **SCA-SDPT3**: Problem (10) is solved by SDPT3 solvers (a second-order solver)
  - **SCA-SCS**: Problem (10) is solved by SCS solvers (a first-order solver)

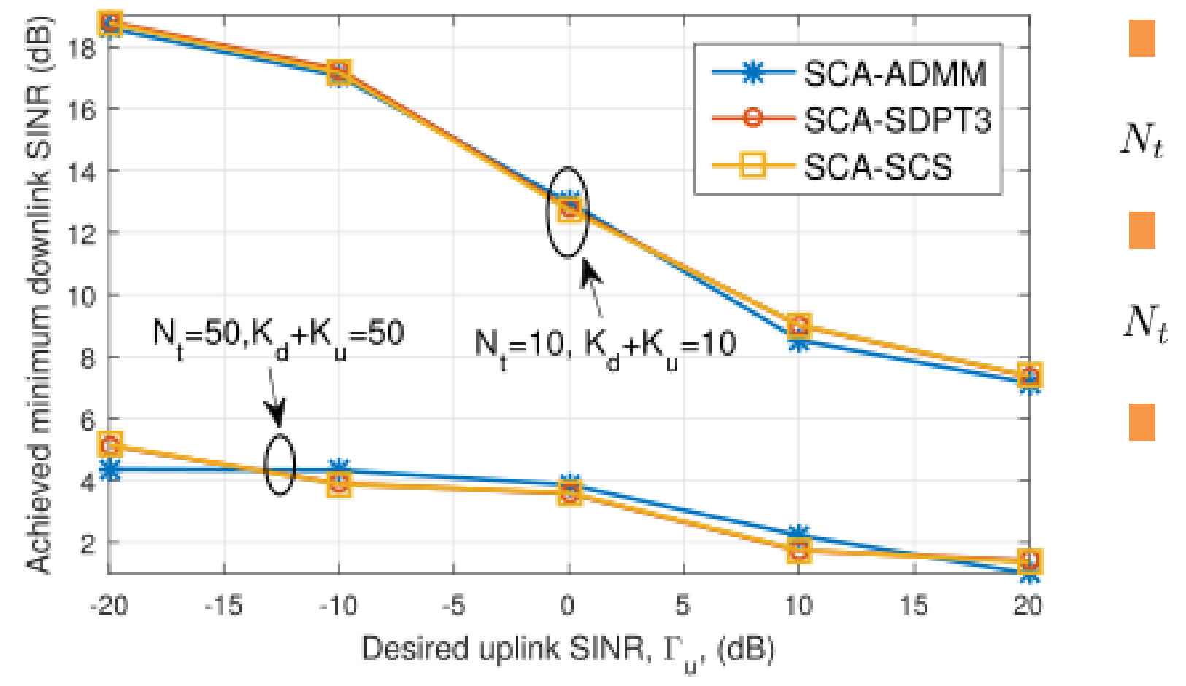


Fig. 1. Achievable downlink SINR vs uplink SINR requirement.

- **Small-size setup**: $p_{u_n} = 0.5$ W. $N_t = N_r = 10$, $K_d = K_u = 5$, $P_i^{BS} = 1$ W
- **Large-size setup:** $p_{u_n} = 1$ W. $N_t = N_r = 50$, $K_d = K_u = 25$, $P_i^{BS} = 2$ W
- For both small-size and large-size systems, the proposed **SCA-ADMM** can obtain similar performance with two baseline schemes.

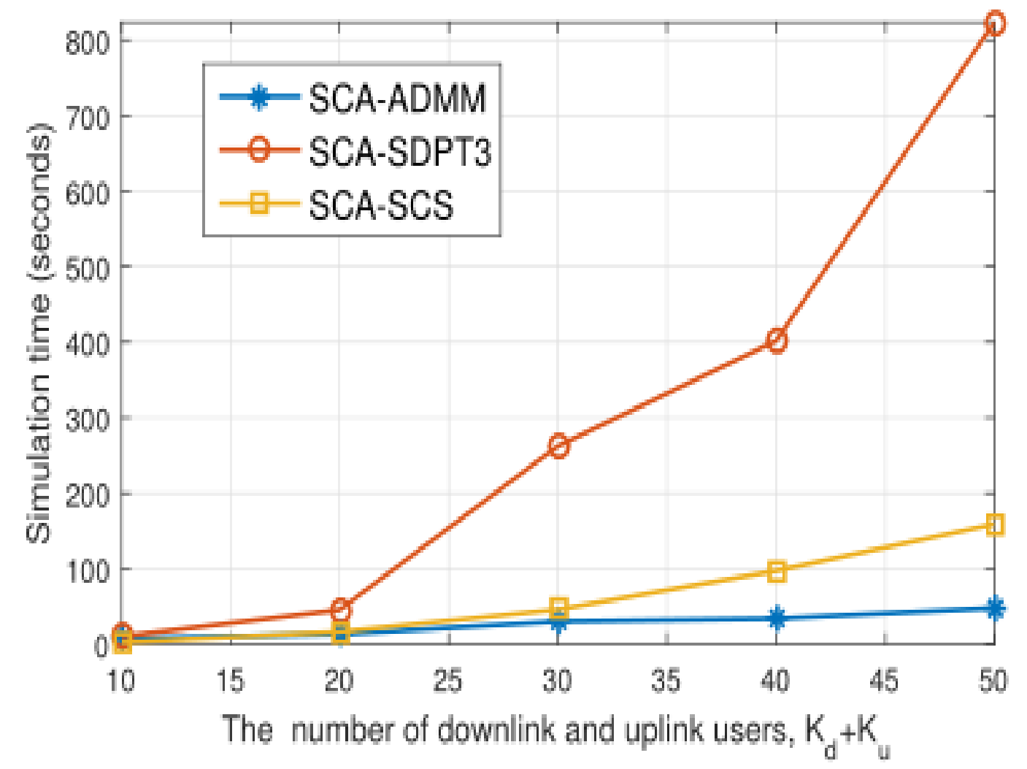


Fig. 2. Simulation time vs the number of users with $N_t = 50$, $N_r = 50$.

- From Fig. 2, the proposed **SCA-ADMM** scheme runs 4 times faster than **SCA-SCS** scheme and 17 times faster than **SCA-SDPT3** when $N_t = 50$.
- The proposed **SCA-ADMM** scheme can significantly reduce the computational complexity and is very suitable for large-scale systems.

Conclusions

- ☐ we have proposed a low-complexity parallel beamforming algorithm to maximize the minimum weighted downlink SINR with uplink SINR constraints and per-antenna constraints in FD systems.
- ☐ The SCA method and ADMM are utilized.
- ☐ Extensive numerical experiments have been carried out to evaluate the performance of our proposed scheme.

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