Dynamic TDD with Imperfect Channel Reciprocity

Soumendu Ghosh

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SPC Lab.
Department of Electrical Communication Engineering
Indian Institute of Science, Bengaluru

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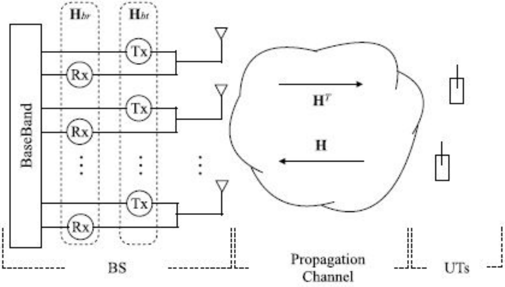
Part I - Modeling of Imperfect Channel Reciprocity

Introduction

- Why do we make perfect reciprocity assumption?



  - In general, massive MIMO systems operate in TDD mode.
  - Here the BS learns the channel via uplink channel training.
  - If channel is reciprocal, no downlink training is needed.
  - It saves the large amount of training overhead required for downlink training.

Introduction

- Why is this assumption not valid?
    - Perfect reciprocity assumption needs the uplink and downlink channels (over-the-air channel) to be identical and the perfect calibration of the RF chains both at the BS and at the users side.
    - The former requirement can be safely assumed [1].
    - However, the transceiver RF chains at both the BS and users' end are never identical.
    - Due to
        - (i.) imperfect clock synchronization
        - (ii.) variable cable lengths of antennas
        - (iii.) manufacturing defects of low noise amplifiers along with other hardware asymmetries
        - (iv.) imperfect calibrations.

Channel Modeling

What it means:

Imperfect Reciprocity: $\mathbf{H}_d \neq \mathbf{H}_u^T$

- **Channel Models**:
    - The uplink channel from the kth user to the ith BS antenna:$h_{u,ik} = u_{t,k} b_{r,i} h_{i,k}$.
    - The downlink between the ith BS antenna and the kth user: $h_{d,ik} = u_{r,k} b_{t,i} h_{ik}$.
    - $u_{t,k}$&$b_{r,i}$ are the complex valued gains associated with the transmit RF chain of the kth user and the receive RF chain of the ith BS antenna, respectively.
    - $u_{t,k}$, $u_{r,k}$, $b_{r,i}$, and $b_{t,i}$ are i.i.d across all antennas and all users with finite nth order moment denoted as $\eta_{u,t,n}$, $\eta_{u,r,n}$, $\eta_{b,r,n}$ and $\eta_{b,t,n}$, respectively.

Calibration Error Modeling

- The BS and all users perform over-the-air calibration of the transmit and receive RF chains to obtain the estimates its associated complex values gain coefficients.
- The downlink channel can be estimated from the uplink channel estimate as [2],

$$\hat{h}_{d,ik} = \left(\frac{\hat{b}_{t,i}}{\hat{b}_{r,i}}\right)\left(\frac{\hat{u}_{r,k}}{\hat{u}_{t,k}}\right)\hat{h}_{u,ik}.$$

- These calibrations are also going to be imperfect, with magnitude calibration errors ($\delta_{b,i}$ & $\delta_{u,k}$) and phase calibration errors ($\phi_{b,i}$ & $\phi_{u,k}$)
- $\delta_{b,i} e^{j\phi_{b,i}} \triangleq \frac{b_{t,i}}{b_{r,i}} \frac{\hat{b}_{r,i}}{\hat{b}_{t,i}}$ & $\delta_{u,k} e^{j\phi_{u,k}} \triangleq \frac{u_{r,k}}{u_{t,k}} \frac{\hat{u}_{t,k}}{\hat{u}_{r,k}}$

Composite Channel Model

Composite downlink channel

$$\mathbf{H}_d = \mathbf{D}_b \hat{\mathbf{H}}_u \mathbf{D}_u \mathbf{A} + \tilde{\mathbf{H}}_u \bar{\mathbf{A}},$$

where, $\mathbf{D}_b \triangleq \text{diag}[\delta_{b,1} e^{j\phi_{b,1}}, \ldots, \delta_{b,N} e^{j\phi_{b,N}}]^T$,

$\mathbf{D}_u \triangleq \text{diag}[\delta_{u,1} e^{j\phi_{u,1}}, \ldots, \delta_{u,K} e^{j\phi_{u,K}}]^T$, $\mathbf{A} = \text{diag}[\sigma_1, \ldots, \sigma_K]$, $\sigma_i = \sqrt{\dfrac{\mathcal{E}_{pi}\beta_i}{N_0 + \mathcal{E}_{pi}\beta_i}}$

and $\tilde{h}_{u,ik} \sim \mathcal{CN}(0, \eta_{b,t,2}\eta_{u,r,2})$ being the i.i.d entries of $\tilde{\mathbf{H}}_d$.

Part II - Dynamic TDD

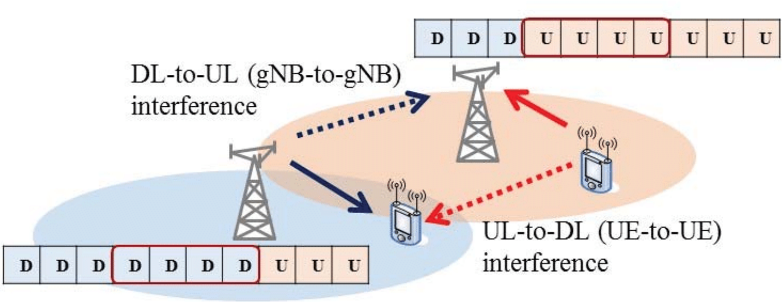
Its advantages and challenges

- In static TDD, all the neighboring cells must transmit in the same direction (UL or DL) on each sub-frame according to a predefined schedule.
- In dynamic TDD, each cell is allowed to configure UL and DL sub-frames adaptively based on its traffic condition, such that adjacent cells in a network are not necessarily operating in the same direction at a given time instant.
- Dynamic TDD can potentially achieve a higher spectrum efficiency (by intelligently scheduling UL and DL sub-frames for each cell based on its traffic condition) compared with static TDD.
- **Challenges**
    - Cross-link interference.
    - Pilot contamination.

System Model

We consider

- L macro-cells
- In each cell K number of single-antenna users are being served by an N antenna massive MIMO BS.



Channel Models

- BS-to-BS [3]:

$$\mathbf{G}_{jn} = \mathbf{G}_{jn}^{\mathrm{NLoS}} + \mathbf{G}_{jn}^{\mathrm{LoS}} = \tilde{\mathbf{R}}_{jn}\bar{\mathbf{G}}_{jn}\tilde{\mathbf{T}}_{jn} + \mathbf{G}_{jn}^{\mathrm{LoS}},$$

  where,

  - $[\mathbf{G}_{jn}^{\mathrm{LoS}}]_{i,j} = \sqrt{\alpha}e^{i\varphi_{i,j}}$
  - $\tilde{\mathbf{R}}_{jn}$ and $\tilde{\mathbf{T}}_{jn}$ are deterministic matrices that characterize the large scale fading and spatial correlation structures at receiving and transmitting antenna arrays.
  - $\bar{\mathbf{G}}_{jn} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_N)$.

UL & DL Receptions

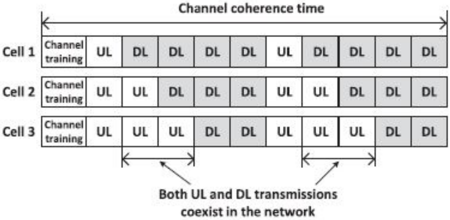
- Then the instantaneous uplink received signal by the j-th ($j \in \mathcal{S}_{ul}$) BS can be written as

$$\mathbf{y}_j^u = \sum_{l \in \mathcal{S}_{ul}} \sum_{k=1}^{K} \sqrt{\mathcal{E}_{lk}\beta_{jlk}}\mathbf{h}_{jlk} s_{lk} + \sum_{n \in \mathcal{S}_{dl}} \sqrt{\rho}_{dl}\mathbf{G}_{jn}\mathbf{P}_n\mathbf{x}_{B,n} + \mathbf{n}_j^{ul}.$$

- The downlink received signal at the kth UE of ith cell can be expressed as

$$y_{ik}^d = \sum_{n \in \mathcal{S}_{dl}} \sqrt{\beta_{ink}}\mathbf{h}_{ink}^H \mathbf{P}_n \mathbf{x}_{B,n} + \sum_{l \in \mathcal{S}_{ul}} \sum_{m=1}^{K} \sqrt{\mathcal{E}_{lm}\eta_{iklm}} g_{iklm} s_{lm} + n_{ik}^d.$$

Channel Estimation



Channel coherence time

Cell 1	Channel training	UL	DL	DL	DL	DL	UL	DL	DL	DL	DL
Cell 2	Channel training	UL	UL	DL	DL	DL	UL	UL	DL	DL	DL
Cell 3	Channel training	UL	UL	UL	DL	DL	UL	UL	UL	DL	DL

Both UL and DL transmissions coexist in the network

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$$y^{ul}_{mlk} = \underbrace{\sqrt{\mathcal{E}_{plk}\beta_{mlk}}\, h_{mlk}\phi_{lk}}_{\text{desired term}} + \underbrace{\sum_{i=1,i\neq k}^{K} \sqrt{\mathcal{E}_{pli}\beta_{mli}}\, h_{mli}\phi_{li}}_{\text{intra-cell interference}} + \underbrace{\sum_{l'\in S_u\setminus l}\sum_{k'=1}^{K} \sqrt{\mathcal{E}_{pl'k'}\beta_{ml'k'}}\, h_{ml'k'}\phi_{l'k'}}_{\text{multi-cell interference}} + n^{ul}_{mlk}.$$

- $\hat{h}_{mlk} = \dfrac{\sqrt{\mathcal{E}_{plk}\beta_{mlk}}}{\sigma^2 + \sum\limits_{l'\in S_u} \mathcal{E}_{pl'k'}\beta_{ml'k'}} y'_{mlk}$, with $\mathbb{E}[|\hat{h}_{mlk}|^2] = \dfrac{\mathcal{E}_{plk}\beta_{mlk}}{\sigma^2 + \sum\limits_{l'\in S_u} \mathcal{E}_{pl'k'}\beta_{ml'k'}}$.
- Efficient techniques are required to handle pilot contamination.

BS-BS Interference Cancellation

- **Estimation Based Interference Cancellation Scheme**
  - Here we have assumed that the transmitted symbol vector from the active downlink BSs are shared among all the BSs. Using that downlink transmitted symbol vector we estimate the effective channel,hence the effective BS-BS interference.
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$$\begin{aligned}
\bar{\mathbf{y}}^{u}_{j,sic} &= \mathbf{y}^{u}_{j} - \sum_{n \in \mathcal{S}_{dl}} \sqrt{\rho}_{dl} \hat{\mathbf{G}}_{jn} \mathbf{P}_{n} \mathbf{x}_{B,n} \\
&= \sum_{l \in \mathcal{S}_{ul}} \sum_{k=1}^{K} \sqrt{\mathcal{E}_{lk}\beta_{jlk}} \mathbf{h}_{jlk} s_{lk} + \sum_{n \in \mathcal{S}_{dl}} \sqrt{\rho}_{dl} \tilde{\mathbf{G}}_{jn} \mathbf{P}_{n} \mathbf{x}_{B,n} + \mathbf{n}^{ul}_{j} \\
&= \sum_{k=1}^{K} \sqrt{\mathcal{E}_{jk}\beta_{jjk}} \mathbf{h}_{jjk} s_{jk} + \sum_{l \in \mathcal{S}_{ul} \setminus j} \sum_{k=1}^{K} \sqrt{\mathcal{E}_{lk}\beta_{jlk}} \mathbf{h}_{jlk} s_{lk} + \underbrace{\sum_{n \in \mathcal{S}_{dl}} \sqrt{\rho}_{dl} \tilde{\mathbf{G}}_{jn} \mathbf{P}_{n} \mathbf{x}_{B,n}}_{\text{interference due to SIC error}} + \mathbf{n}^{ul}_{j}.
\end{aligned}$$

BS-BS Interference Cancellation

- **Genie Aided Interference Cancellation Scheme**

  In genie-aided method we assume that the information of the interfering term from the neighboring DL-BS is available at the UL-BS of the concerned cell. Therefore, the received uplink signal leads to an optimal achievable uplink rate of the system.

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$$\begin{aligned}\bar{\mathbf{y}}^{u}_{j,genie} &= \sum_{l\in\mathcal{S}_{ul}}\sum_{k=1}^{K}\sqrt{\mathcal{E}_{lk}\beta_{jlk}}\mathbf{h}_{jlk}s_{lk} + \mathbf{n}_j^{ul} \\ &= \sum_{k=1}^{K}\sqrt{\mathcal{E}_{jk}\beta_{jjk}}\mathbf{h}_{jjk}s_{jk} + \sum_{l\in\mathcal{S}_{ul}\setminus j}\sum_{k=1}^{K}\sqrt{\mathcal{E}_{lk}\beta_{jlk}}\mathbf{h}_{jlk}s_{lk} + \mathbf{n}_j^{ul}.\end{aligned}$$

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Thank You