Uplink and Downlink Rate Analysis of a Full-Duplex C-RAN with Radio Remote Head Association

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Outline

Motivation for C-RAN

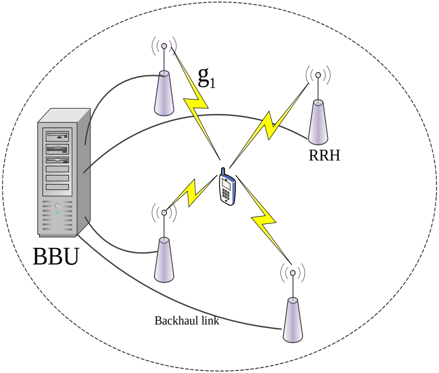
- Consider the traditional cellular systems
  - ✓ Architecture: base-stations (BSs) located at the cell center and spatially distributed users across the cell
  - ✓ Challenge: dead spots within the cell
- A promising solution is to utilize distributed BSs across the cell: ***C-RANs***
  - ✓ C-RANs can accommodate the 5G requirements [1]
    - ✓ High energy-efficiency transmission
    - ✓ Improved spectral utilization
    - ✓ Reduce capital/operating expenses for cellular network deployment

[1] Z. Ding and H. V. Poor, “The use of spatially random base stations in cloud radio access networks," *IEEE Signal Process. Lett.*, vol. 20, pp.1138-1141, Nov. 2013.

Cloud Radio Access Network: Basics

Key ideas:

- ✓ Deploy a pool of distributed radio units called remote radio heads (RRHs)
- ✓ Connect RRHs with a centrally located baseband unit (BBU) via dedicated high-speed backhaul links
- ✓ BBU is capable of sophisticated processing
- ✓ Only low cost RRHs need to be deployed for improving the coverage as well as the capacity of the network



Full-duplex C-RAN

Why full-duplex C-RAN

- In previous works, only UL or DL performance have been considered: half-duplex FDD/TDD
- Half-duplex FDD/TDD suffers from spectral inefficiency
- Potential avenue to achieve higher spectral efficiency is to leverage full-duplex [2]
- Full-duplex communication is capable of supporting simultaneous UL and DL transmissions
- Full-duplex operation is now an efficient practical solution [3]

[2] A. Sabharwal, et al., "In-band full-duplex wireless: Challenges and opportunities," *IEEE J. Sel. Areas Commun.,* vol. 32, pp. 1637-1652, Sep. 2014.

[3] M. Duarte, "Full-duplex wireless: Design, implementation and characterization," Ph.D. dissertation, Dept. Elect. and Computer Eng., Rice University, Houston, TX, 2012.

Full-duplex C-RAN Challenges

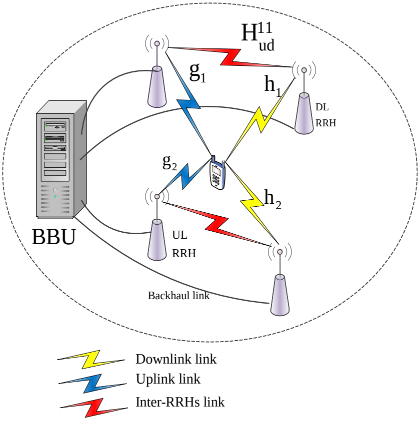
- Loopback interference (LI)
  - If not mitigated substantially, can cause serious performance degradation
  - LI mitigation/suppression methods [4]
    - ✓ Antenna domain, e.g., directional antennas and antenna separation
    - ✓ Time-domain cancellation
    - ✓ Spatial suppression
  - Modeling the residual LI channel [4]: Rayleigh flat fading
- Inter-RRH interference: Interference between UL and DL RRHs
  - Inter-RRH interference mitigation/suppression

[4] T. Riihonen, et al., "Mitigation of loopback self-interference in full-duplex MIMO relays," *IEEE Trans. Signal Process.*, vol. 59, pp. 5983-5993, Dec. 2011.

System Model

Network Model and Assumptions:

- A full-duplex user U, a group of spatially distributed RRHs to jointly support U for both DL and UL, and a BBU
- RRHs are modeled as a homogeneous PPP, $\Phi = \{x_k\}$ with density λ from which
  - ✓ $100p_{\mathrm{D}}$% are deployed to assist the DL Tx: $\Phi_{\mathrm{d}} = \{x_k \in \Phi : B_k(p_{\mathrm{D}}) = 1\}$
  - ✓ $100(1 - p_{\mathrm{D}})$% are deployed for the UL Rx: $\Phi_{\mathrm{u}} = \{x_k \in \Phi : B_k(p_{\mathrm{D}}) = 0\}$
- RRHs are equipped with $M \geq 1$ antennas and U is equipped with two antennas



RRH Association Schemes

All RRH Association (ARA):

- All DL RRHs cooperatively transmit their signal to the full-duplex User

$$\mathrm{SINR}_{\mathrm{d}}^{A} = \frac{\sum_{i\in\Phi_{\mathrm{d}}} P_b \ell(x_i) |\mathbf{h}_i^{\dagger}\mathbf{w}_{t,i}|^2}{\underbrace{P_u|h_{\mathrm{LI}}|^2}_{\text{Loopback interference}} + 1}$$

- All the corresponding UL RRHs deliver signals from U to the BBU

$$\mathrm{SINR}_{\mathrm{u}}^{A} = \frac{\sum_{j\in\Phi_{\mathrm{u}}} P_u \ell(x_j) |\mathbf{w}_{r,j}^{\dagger}\mathbf{g}_j|^2}{\underbrace{\sum_i \sum_j P_b \ell(x_j, x_i) |\mathbf{w}_{r,j}^{\dagger}\mathbf{H}_{\mathrm{ud}}^{ji}\mathbf{w}_{t,i}|^2}_{\text{Inter-RRHs interference}} + \|\mathbf{w}_{r,j}\|^2},$$

with $\ell(x_j, x_i) = \|x_j - x_i\|^{-\mu}$ and $\mu > 2$ is path loss exponent

RRH Association Schemes

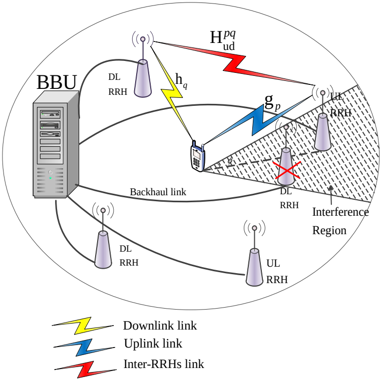
Single Best RRH Association (SRA):

- UL RRH with best channels to U is selected:

$$\mathrm{SINR}_{\mathrm{u}}^{\mathrm{S}} = \frac{P_u \ell(x_p)|\mathbf{w}_{r,p}^{\dagger}\mathbf{g}_p|^2}{\underbrace{P_b \ell(x_p, x_q)|\mathbf{w}_{r,p}^{\dagger}\mathbf{H}_{\mathrm{ud}}^{pq}\mathbf{w}_{t,q}|^2}_{\text{Inter-RRHs interference}} + \|\mathbf{w}_{r,p}\|^2}.$$

- A sectorized interference region (IR) of angle $\pm\phi$ around the $U-p$ axis is adopted. No DL RRH transmission is allowed within the IR:

$$\mathrm{SINR}_{\mathrm{d}}^{\mathrm{S}} = \frac{P_b \ell(x_q)|\mathbf{h}_q^{\dagger}\mathbf{w}_{t,q}|^2}{\underbrace{P_u|h_{\mathrm{LI}}|^2}_{\text{Loopback interference}} + 1}.$$



Optimal Processing for SRA Scheme

- **Objective**:
  - Jointly design $\mathbf{w}_{r,p}$ and $\mathbf{w}_{t,q}$ to maximize the sum rate of SRA scheme
- **Optimization problem (OP)**

$$\max_{\mathbf{w}_{t,q},\mathbf{w}_{r,p}} \quad \mathcal{R}_{\text{sum}}^{\text{FD}} = \ln\left(1 + a_1\|\mathbf{h}_q^{\dagger}\mathbf{w}_{t,q}\|^2\right) + \ln\left(1 + \frac{a_2\|\mathbf{w}_{r,p}^{\dagger}\mathbf{g}_p\|^2}{a_3\|\mathbf{w}_{r,p}^{\dagger}\mathbf{H}_{\text{ud}}^{pq}\mathbf{w}_{t,q}\|^2 + \|\mathbf{w}_{r,p}\|^2}\right),$$

$$\text{s.t.} \quad \|\mathbf{w}_{r,p}\| = \|\mathbf{w}_{t,q}\| = 1,$$

where $a_1 = \frac{P_b \ell(x_q)}{P_u|h_{\text{LI}}|^2+1}$, $a_2 = P_u\ell(x_p)$, and $a_3 = P_b\ell(x_p, x_q)$.

Optimal Processing for SRA Scheme

- $\mathbf{w}_{r,p}$: Fixing $\mathbf{w}_t$, we get a generalized Rayleigh ratio problem whose solution is

$$\mathbf{w}_{r,p} = \frac{\left(a_3 \mathbf{H}_{\text{ud}}^{pq} \mathbf{w}_{t,q} \mathbf{w}_{t,q}^{\dagger} \mathbf{H}_{\text{ud}}^{pq\dagger} + \mathbf{I}\right)^{-1} \mathbf{g}_p}{\left\| \left(a_3 \mathbf{H}_{\text{ud}}^{pq} \mathbf{w}_{t,q} \mathbf{w}_{t,q}^{\dagger} \mathbf{H}_{\text{ud}}^{pq\dagger} + \mathbf{I}\right)^{-1} \mathbf{g}_p \right\|}.$$

- Substituting the $\mathbf{w}_{r,p}$ into OP after some algebraic manipulation we get

$$\begin{aligned} \max_{\mathbf{w}_{t,q}} \quad & \text{trace}(\boldsymbol{h}_q^{\dagger} \boldsymbol{W}_t \boldsymbol{h}_q) \\ \text{s.t.} \quad & \text{trace}(\boldsymbol{W}_t(\mathbf{H}_{\text{ud}}^{pq\dagger} \boldsymbol{g}_p \boldsymbol{g}_p^{\dagger} \mathbf{H}_{\text{ud}}^{pq} - \alpha\, \mathbf{H}_{\text{ud}}^{pq\dagger} \mathbf{H}_{\text{ud}}^{pq})) = \frac{\alpha}{a_3}, \\ & \boldsymbol{W}_t \succeq 0, \quad \text{trace}(\boldsymbol{W}_t) = 1, \quad \text{rank}(\boldsymbol{W}_t) = 1, \end{aligned}$$

- By dropping the rank-1 constraint, the resulting problem becomes a semidefinite program, whose solution $\mathbf{W}_t$ can be found by using appropriate solvers like CVX.

Suboptimum Designs

- **ZF/MRT Scheme**:

  The beamforming vectors are derived as:

  - $\mathbf{w}_{t,q}^{\mathrm{MRT}} = \frac{\mathbf{h}_q}{\|\mathbf{h}_q\|}$
  - $\mathbf{w}_{r,p}^{\mathrm{ZF}}$ is obtained by solving the following problem

$$\max_{\|\mathbf{w}_{r,p}\|=1} \quad |\mathbf{w}_{r,p}\mathbf{g}_p|^2, \quad \text{s.t. } \mathbf{w}_{r,p}^{\dagger}\mathbf{H}_{\mathrm{ud}}^{pq}\mathbf{h}_q = 0$$

$$\Rightarrow \mathbf{w}_{r,p}^{\mathrm{ZF}} = \frac{\mathbf{A}\mathbf{g}_p}{\|\mathbf{A}\mathbf{g}_p\|}, \quad \mathbf{A} \triangleq \mathbf{I} - \frac{\mathbf{H}_{\mathrm{ud}}^{pq}\mathbf{h}_q\mathbf{h}_q^{\dagger}\mathbf{H}_{\mathrm{ud}}^{pq\dagger}}{\|\mathbf{H}_{\mathrm{ud}}^{pq}\mathbf{h}_q\|^2}$$

- **MRC/MRT Scheme**

  The beamforming vectors are set to match the UL and DL channels, i.e.,

  - $\mathbf{w}_{t,q}^{\mathrm{MRT}} = \frac{\mathbf{h}_q}{\|\mathbf{h}_q\|}$
  - $\mathbf{w}_{r,p}^{\mathrm{MRC}} = \frac{\mathbf{g}_p}{\|\mathbf{g}_p\|}$

Average Uplink nd Downlink Rate Analysis

For the considered C-RAN system we are interested in:

- Study the average sum rate for
  - ARA scheme with MRC/MRT processing
  - SRA scheme with MRC/MRT processing
  - SRA scheme with ZF/MRT processing

$$\mathcal{R}_{\text{sum}}^{\text{FD}} = \mathcal{R}_{\text{u}} + \mathcal{R}_{\text{d}} = \mathbb{E}\left\{\ln\left(1 + \text{SINR}_{\text{u}}\right)\right\} + \mathbb{E}\left\{\ln\left(1 + \text{SINR}_{\text{d}}\right)\right\}$$

- Investigate the sum rate gains as compared to the half-duplex counterpart

Key Results of the Average Sum Rate Analysis

- **ZF/MRT processing**
  - **Proposition 1** develops an expression for the the average sum rate achieved by the SRA scheme.
  - **Proposition 3** provides an expression for the the average DL rate achieved by the ARA scheme.
- **MRC/MRT processing**
  - **Proposition 2** develops an expression for the average UL rate achieved by the SRA scheme.
  - **Proposition 1 and 2** develop an expression for the average sum rate achieved by the SRA scheme.
  - **Proposition 3** provides an expression for the average DL rate achieved by the ARA scheme.

Reference System and Simulation Parameters

- **Reference system: C-RAN with half-duplex user**
  - Orthogonal time slots for DL and UL transmissions with

$$R_{\text{sum}}^{\text{HD}} = \tau \mathbb{E}\left\{ \ln(1 + \sum_{i \in \Phi_{\text{d}}} P_b \ell(x_i) \|\mathbf{h}_i^{\dagger} \mathbf{w}_{t,i}\|^2) \right\} + (1-\tau)\mathbb{E}\left\{ \ln(1 + \sum_{j \in \Phi_{\text{u}}} P_u \ell(x_j) \|\mathbf{w}_{r,j}^{\dagger} \mathbf{g}_j\|^2) \right\}.$$

- **Simulation parameters**
  - The simulations adopt parameters of a LTE-A network[5]
    - ✓ The power spectral density of receiver noise: -120 dBm/Hz
    - ✓ The path loss exponent: $\alpha = 3$

[5] "Radio frequency (RF) requirements for LTE pico node B," ETSI TR 136 931 V9.0.0, Tech. Rep., May 2011.

Rate Region of the ARA and SRA Schemes

- The ARA scheme results in a rate region that is strongly biased towards UL or DL
- But using the SRA scheme results in a more balanced rate region
- SRA scheme with optimal beamforming can achieve up to 89% average sum rate gains as compared to the half-duplex SRA counterpart
- SRA scheme with ZF/MRT beamforming can achieve up to 80% average sum rate gains as compared to the half-duplex SRA counterpart

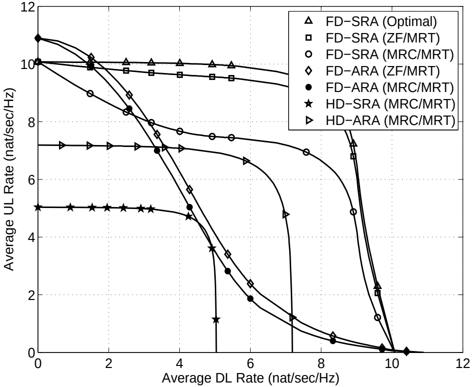


Figure: Rate region of the ARA and SRA schemes for full-duplex and half-duplex modes of operation ($M = 3$, $P_u = 23$ dBm, $P_b = 23$ dBm, and $\lambda = 0.001$).

The Impact of the IR Region Parameter ϕ on the Sum Rate

- Increasing the ϕ decreases the number of DL RRHs and consequently the DL rate.
- The UL rates of optimum and ZF/MRT designs remain constant to produce an overall sum rate decrease as ϕ is increased.
- On the contrary, increasing ϕ improves the performance of MRC/MRT because the inter-RRH interference between the selected UL RRH and DL RRH is reduced.
- Clearly, increasing ϕ beyond its optimum value does not improve the sum rate of MRC/MRT processing due to the fact that there may not be sufficient number of DL RRH inside the selection region.

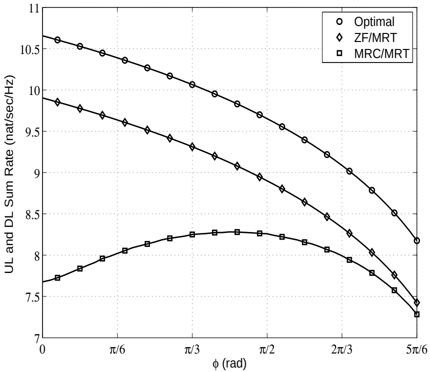


Figure: Average sum rate versus ϕ with different beamforming designs ($M = 2$, $P_u = 10$ dBm, $P_b = 10$ dBm, and $\sigma_{aa}^2 = -30$ dBm).

Summary

We studied the average sum rate of a C-RAN with randomly distributed multiple antenna UL and DL RRHs communicating with a full-duplex user:

- The SRA scheme achieves a superior performance as compared to the ARA scheme
- For a fixed value of LI power, the SRA scheme with optimal and ZF/MRT processing can ensure a balance between maximizing the average sum rate and maintaining an acceptable fairness level between UL/DL transmissions
- Full-duplex transmissions can achieve higher data rates as compared to half-duplex mode of operation, if proper RRH association and beamforming are utilized and the residual LI is sufficiently small

Thank you

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