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Cooperative versus Full-Duplex Communication in Cellular Networks: A Comparison of the Total Degrees of Freedom

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Outline

- Introduction
- Full-duplex system
- Cooperative system
- Cooperative full-duplex system
- DoF Comparison and Conclusion

Introduction

Cellular Full-duplex Transmission

- **Advantages:**
  - Increases throughput and system capacity.
  - Allows more flexible usage of the spectrum.
  - Reduces the delay in the feedback of control information, channel state information and acknowledgment messages.

- **Challenges**
  - Self-interference; over 100 dB suppression is required.
  - Inter-user interference; careful design of efficient interference management techniques is required.

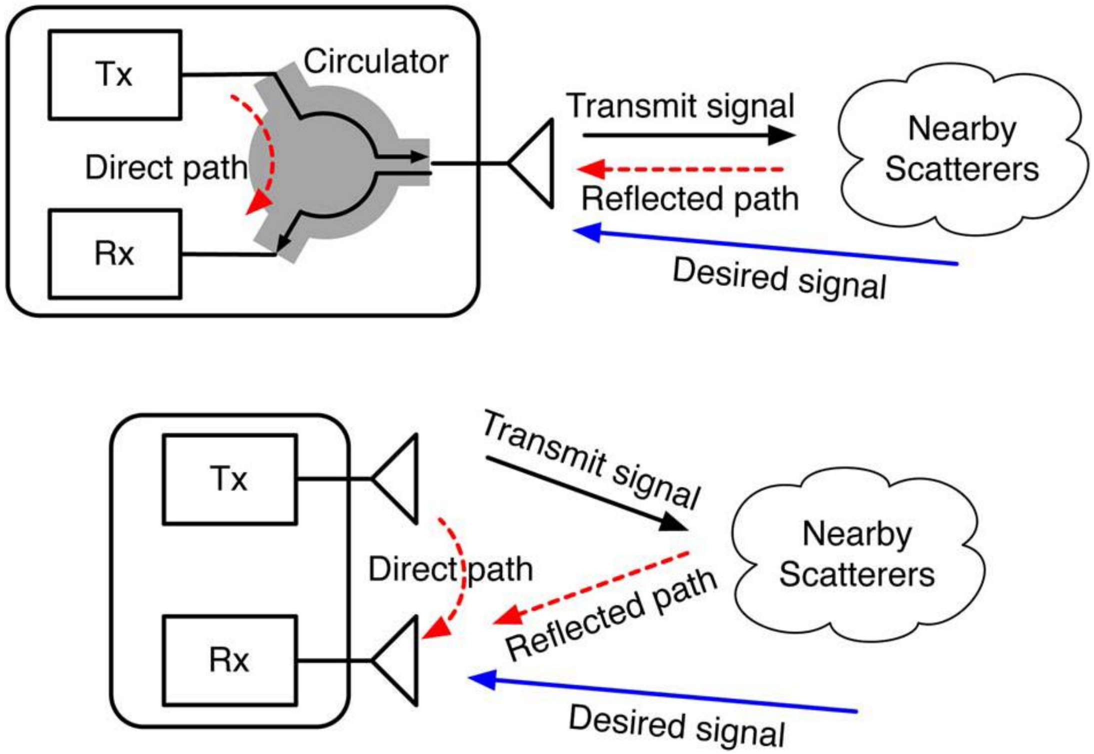
Implementation of full-duplex transceivers

Shared antenna

Same antenna used both for transmission and reception

Separate antenna

Propagation-domain isolation can be used for self-interference cancellation



*Shared- and separate -antenna full-duplex transceivers**

* A. Sabharwal, P. Schniter, Dongning Guo, D.W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *IEEE JSAC*, vol. 32, pp. 1637–1652, September 2014.

Introduction

Related work

- In [1], single-cell system with full-duplex shared antenna BS and multiple half-duplex UEs, the DoF of the system are doubled.

- In [2], single-cell system with full-duplex separate antenna BS (M_T,M_R) and multiple half-duplex UEs achieves higher DoF than a half-duplex system employing max(M_T,M_R) antennas.

[1] S.H. Chae and S.H. Lim, "Degrees of freedom of cellular networks: Gain from full-duplex operation at a base station," in IEEE Global Communications Conference (GLOBECOM), Austin, TX, December 2014, pp. 4048–4053.

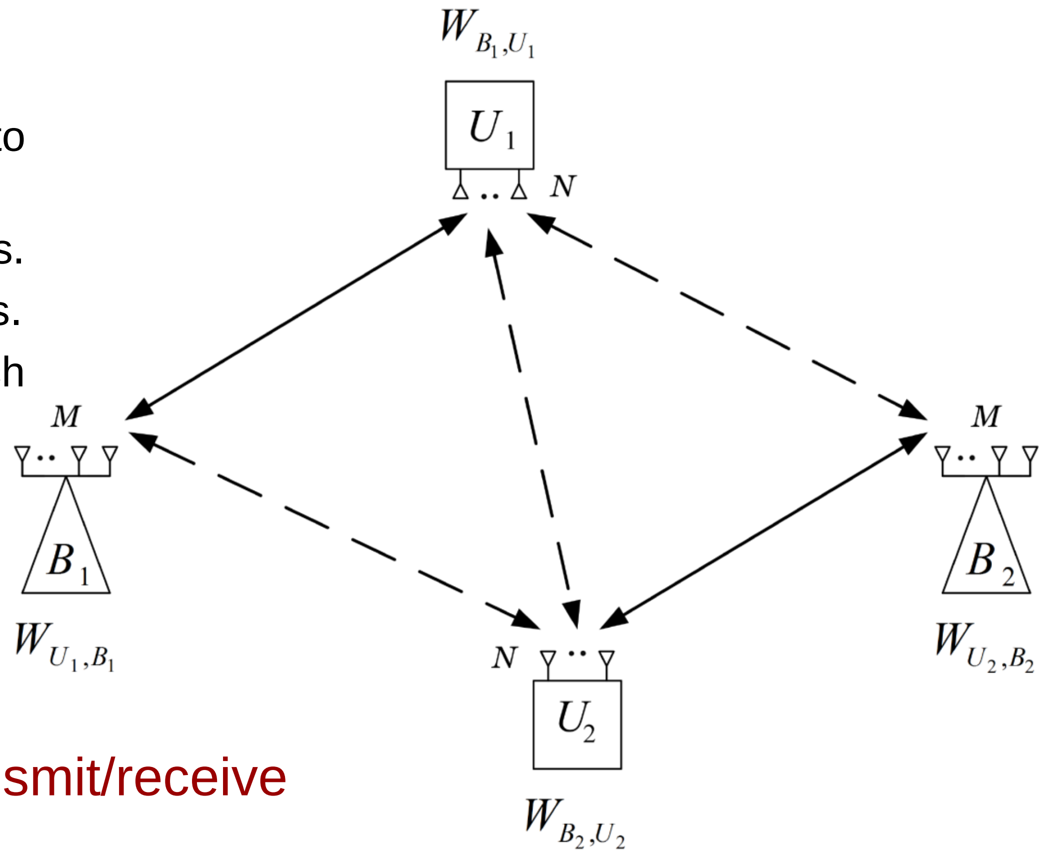
[2] K. Kim, S. Jeon, and D.K. Kim, "The feasibility of interference alignment for full-duplex MIMO cellular networks," IEEE Communications Letters, vol. 19, no. 9, pp. 1500–1503, September 2015.

For a given number of antennas at each node, what is the DoF gain that can be achieved by full-duplex operation in cellular systems, e.g., a two-cell system?

Full-Duplex System

System Model

- Two-cell system
- Each BS uses orthogonal resources to communicate with its attached UEs.
- Each BS has *M* full-duplex separate antennas.
- Each UE has *N* full-duplex separate antennas.
- Perfect self-interference cancellation at each node.
- No interference between the BSs
- Inter-cell and inter-UE interference



What is the **optimal** allocation of transmit/receive antennas at each node?

Total Degrees of Freedom

- The total DoF of a network is defined as $D = \lim_{\mathrm{SNR} \to \infty} \frac{C(\mathrm{SNR})}{\log(1 + \mathrm{SNR})}$
- The DoF represents the rate of growth of network capacity with the logarithm of the signal-to-noise ratio.
- In most networks, the DoF represents the number of interference-free streams that can be transmitted in the network.
- The optimal antenna allocation (M_T, M_R, N_T, N_R) is chosen to maximize the total DoF by solving

$$
\begin{aligned}
D = \max_{M_T, M_R, N_T, N_R} \quad & \lim_{\mathrm{SNR} \to \infty} \frac{C(\mathrm{SNR}, M_T, M_R, N_T, N_R)}{\log(\mathrm{SNR})} \\
\text{subject to} \quad & M_T + M_R = M \\
& N_T + N_R = N
\end{aligned}
$$

Equivalent System Model

d_f : DoF of downlink

d_r : DoF of uplink

$D = 2\, d_f + 2\, d_r$

- Separating the transmit and receive sections of each transceiver:

  Equivalent system:

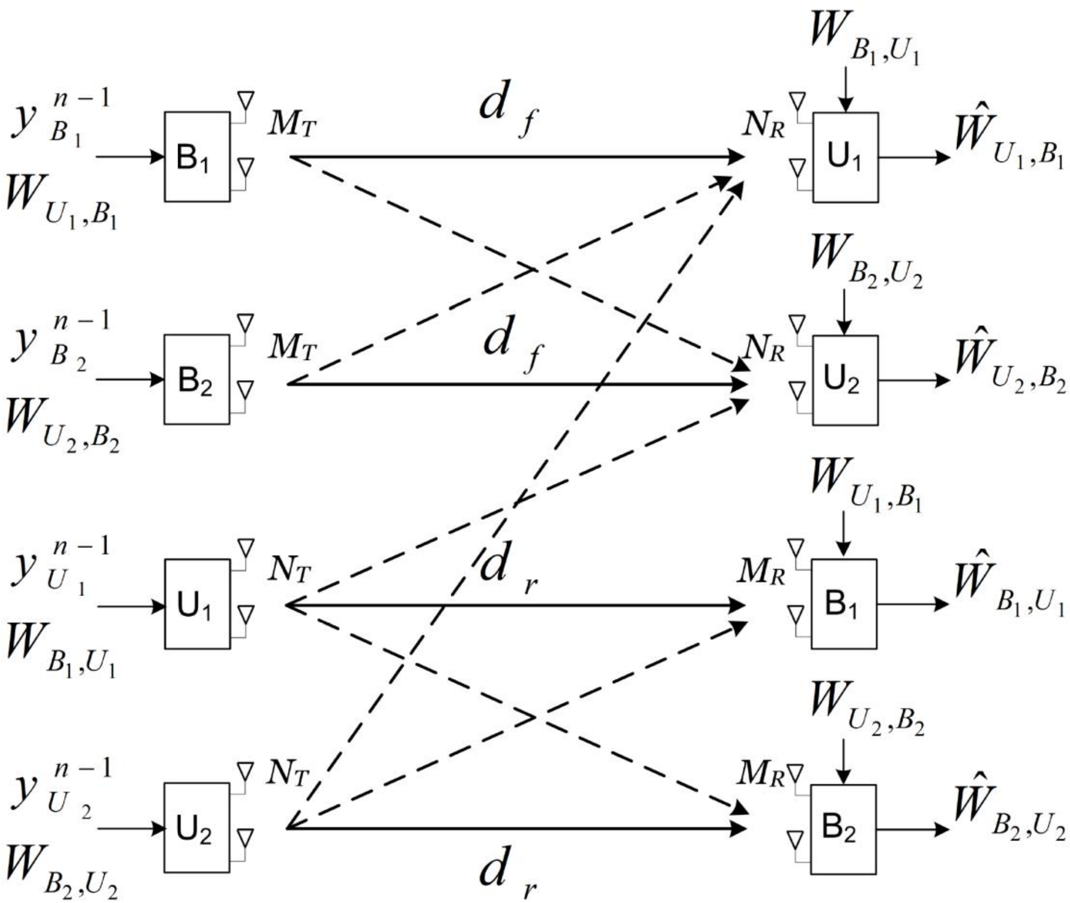
  4-user partly-connected IC

Encoder

$$x_{P_i}(n) = \mathcal{E}_{P_i}\left(W_{Q_i,P_i}, \mathbf{y}_{P_i}^{n-1}\right)$$

Decoder

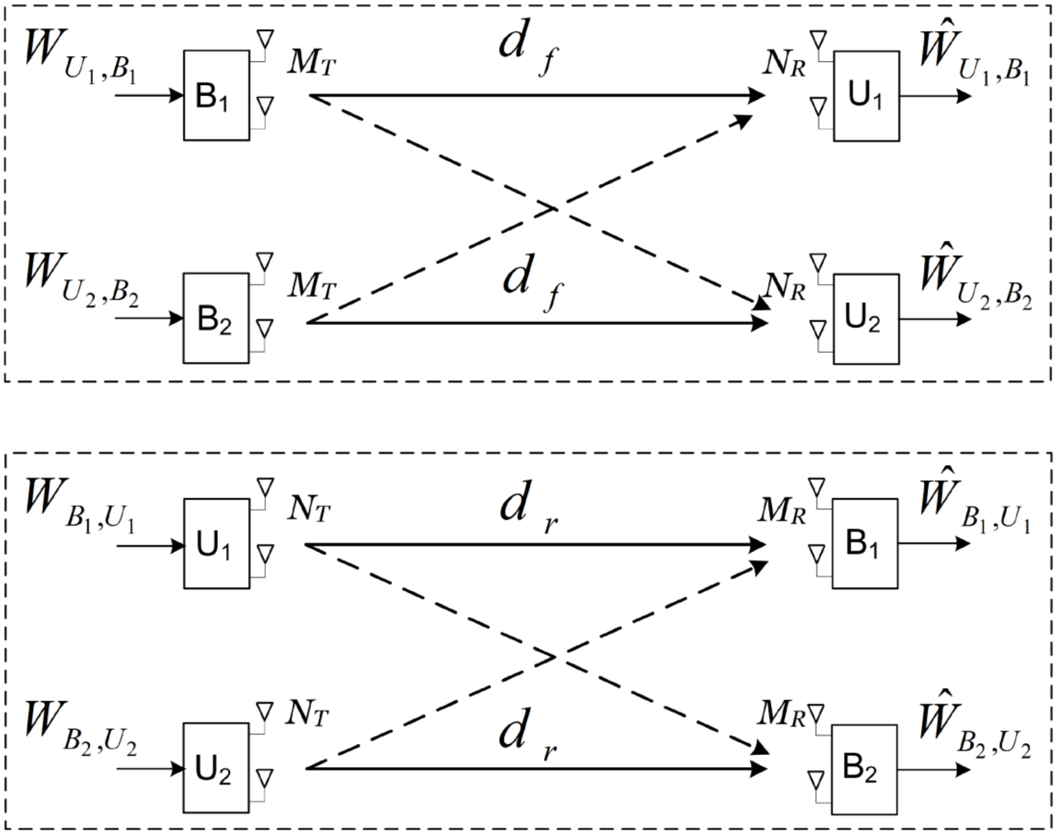
$$\hat{W}_{Q_i,P_i} = \mathcal{D}_{Q_i}\left(W_{P_i,Q_i}, \mathbf{y}_{Q_i}^{L}\right)$$



Bounding the DoF of the system

Eliminating inter-UE inference:

$$2d_f \leq \min\{2M_T, 2N_R, \max\{M_T, N_R\}\}$$
$$2d_r \leq \min\{2N_T, 2M_R, \max\{N_T, M_R\}\}$$



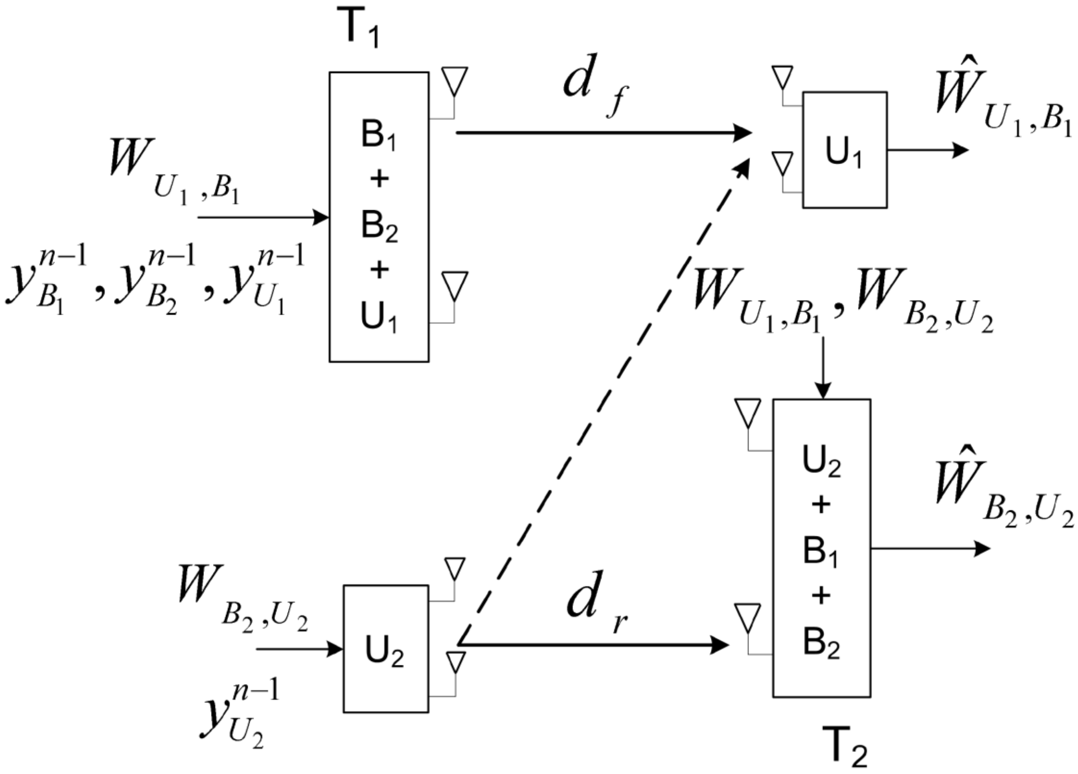
Bounding the DoF of the system

Eliminating messages from B_2 and U_1

Grouping B_1, B_2, and U_1 transmitters

Grouping B_1, B_2, and U_2 receivers

$$d_f + d_r \leq \max\{N_T, N_R\}$$



Full-Duplex System

Bounding the DoF of the system

The total DoF can be bounded by solving

$$
\begin{aligned}
\max_{d_f, d_r, M_T, N_T} \quad & 2d_f + 2d_r \\
\text{subject to} \quad & d_f \leq \min\left\{M_T, N - N_T, \frac{1}{2}\max\{M_T, N - N_T\}\right\} \\
& d_r \leq \min\left\{N_T, M - M_T, \frac{1}{2}\max\{N_T, M - M_T\}\right\} \\
& d_f + d_r \leq \max\left\{N_T, N - N_T\right\} \\
& 0 \leq N_T \leq N \\
& 0 \leq M_T \leq M.
\end{aligned}
$$

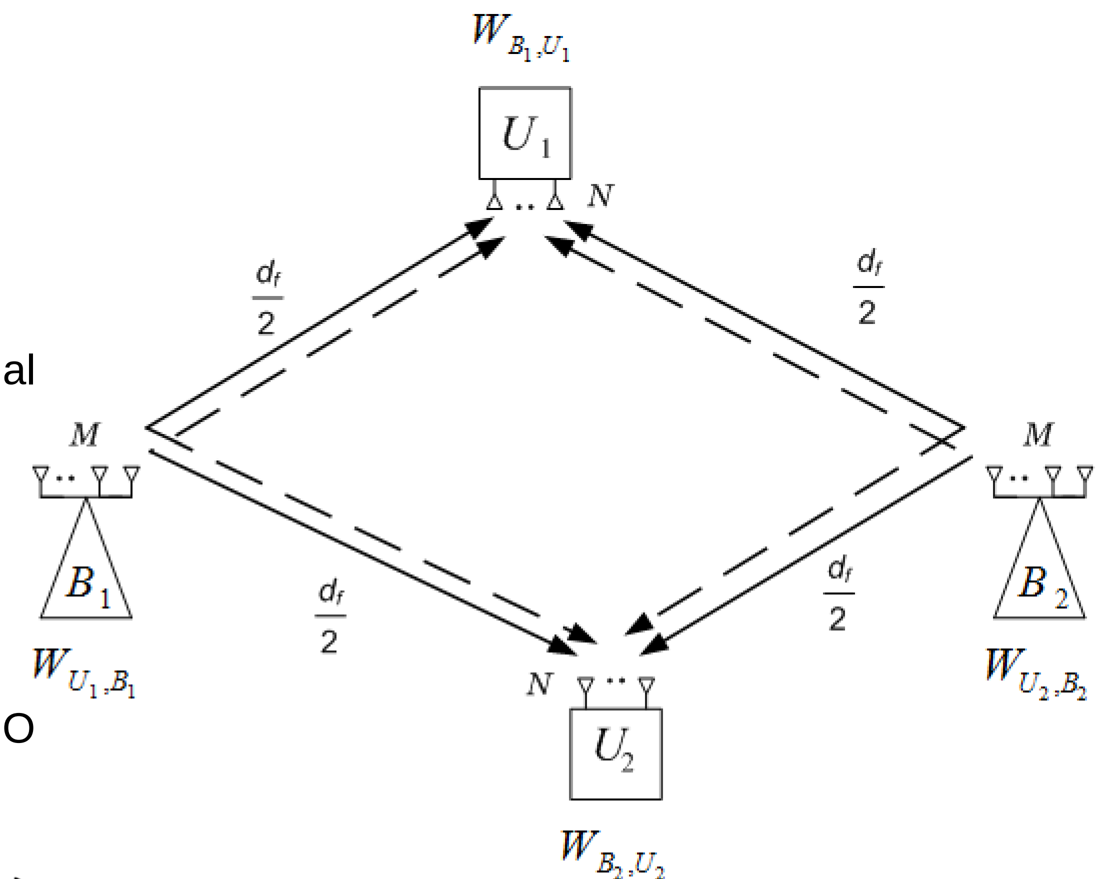
A closed-form solution was obtained to the above non-convex problem

$$
D_{FD} \leq \begin{cases} \min\left\{2M, \frac{2}{3}M + \frac{2}{3}N, \frac{4}{3}N\right\} & 0 \leq M < \frac{7}{6}N \\ \min\left\{\frac{4}{5}M + \frac{2}{5}N, 2N\right\} & M \geq \frac{7}{6}N \end{cases}
$$

Cooperative System

System Model

- Two-cell system
- Each UE is served by both BSs.
- Each BS has *M* antennas.
- Each UE has *N* antennas.
- Uplink and downlink use orthogonal resources
- D= 2df



Results

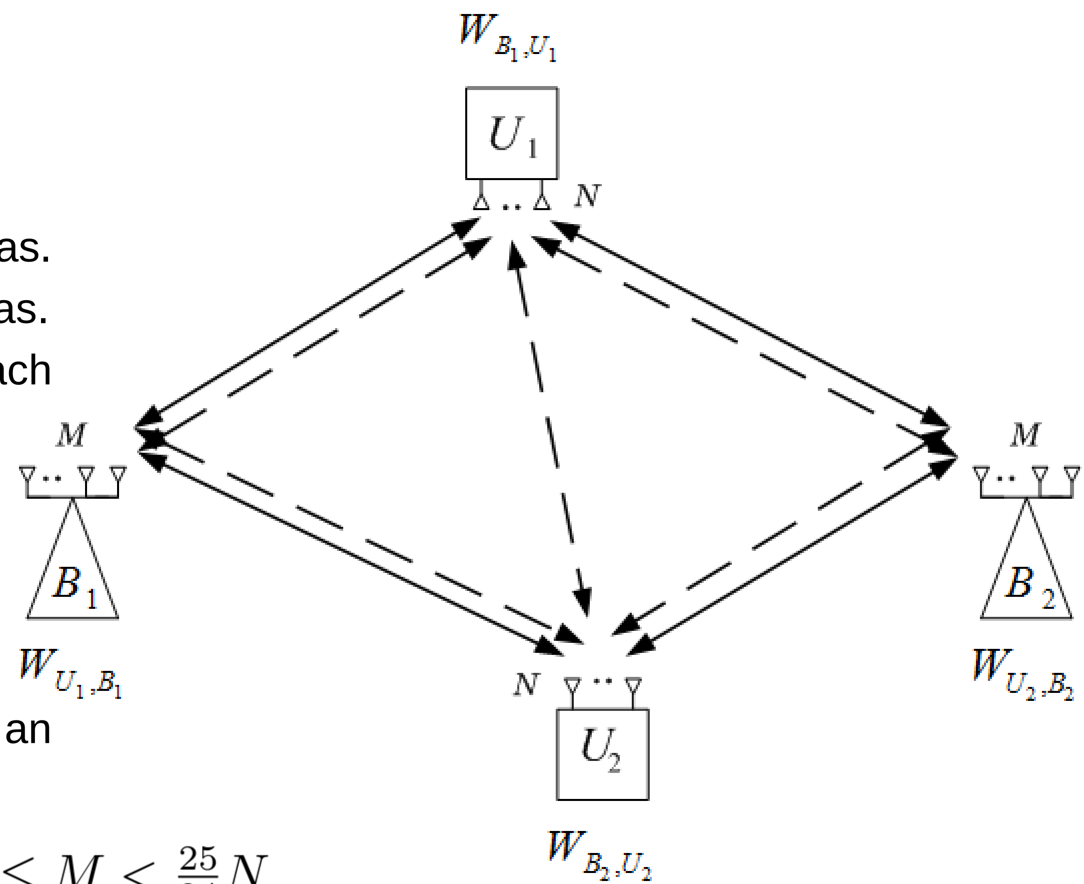
- System is equivalent to a 2-user *MXN* MIMO X-Channel whose DoF is given by

$$D_{\mathrm{HD}}^{\mathrm{X}} = \min\left\{2M, 2N, \frac{4}{3}\max\{M, N\}\right\}$$

Cooperative Full-Duplex System

System Model

- Two-cell system
- The two BSs communicate with the two UEs
- Each BS has *M* full-duplex separate antennas.
- Each UE has *N* full-duplex separate antennas.
- Perfect self-interference cancellation at each node.
- No interference between the BSs
- Inter-cell and inter-UE interference



Results

- Same technique can be used to obtain an upper bound on the DoF of the system

$$D_{FD}^{X} \leq \begin{cases} \min\left\{2M, \frac{4}{5}(M+N), \frac{3}{2}N\right\} & 0 \leq M < \frac{25}{24}N \\ \min\left\{2N, \frac{12}{11}M + \frac{4}{11}N\right\} & M \geq \frac{25}{24}N \end{cases}$$

DoF Comparison

- Full-duplex system

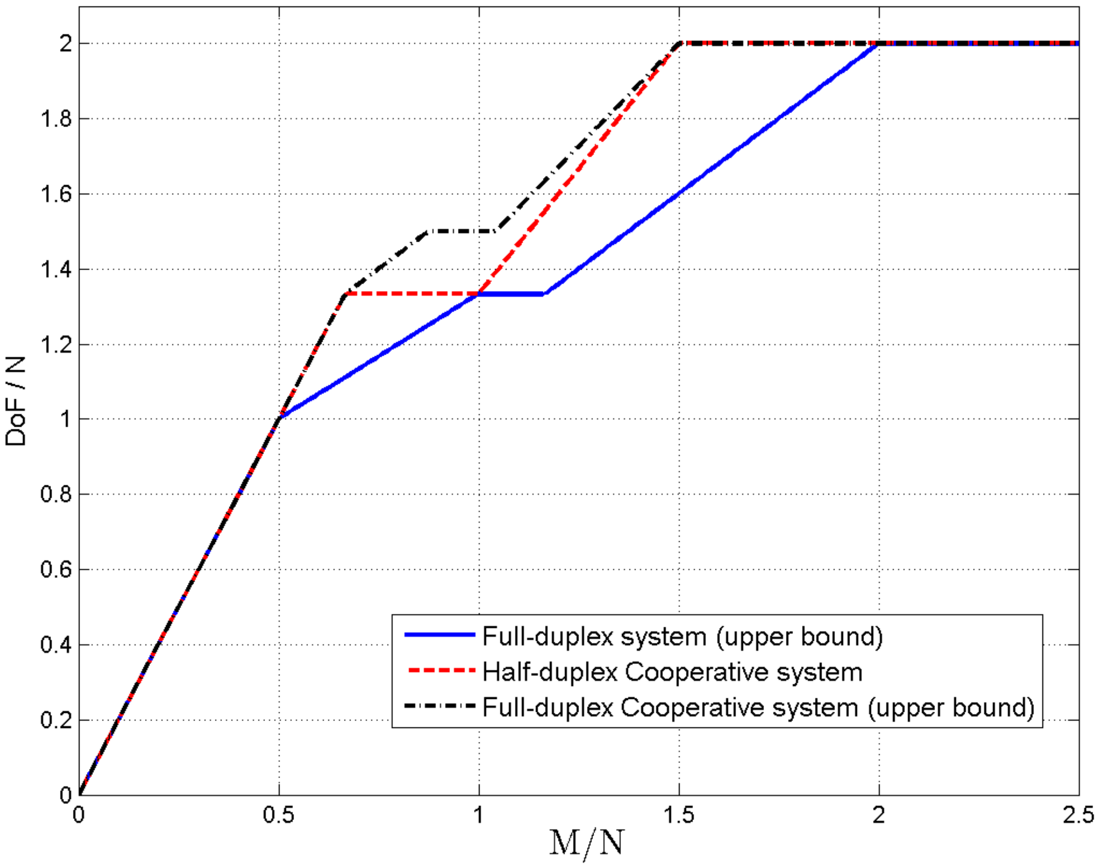
$$D_{FD} \leq \begin{cases} \min\left\{2M, \frac{2}{3}M + \frac{2}{3}N, \frac{4}{3}N\right\} & 0 \leq M < \frac{7}{6}N \\ \min\left\{\frac{4}{5}M + \frac{2}{5}N, 2N\right\} & M \geq \frac{7}{6}N \end{cases}$$

- Cooperative system

$$D_{\mathrm{HD}}^{\mathrm{X}} = \min\left\{2M, 2N, \frac{4}{3}\max\{M, N\}\right\}$$

- Full-duplex cooperative system

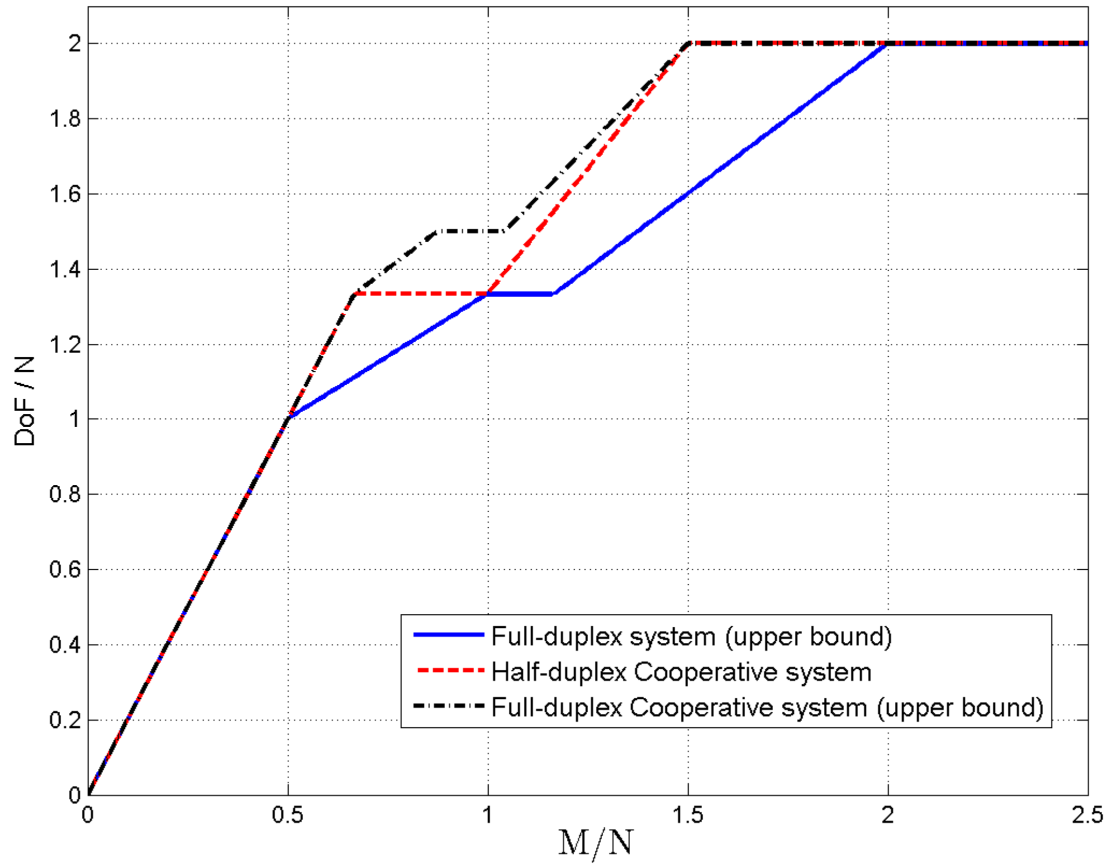
$$D_{FD}^{X} \leq \begin{cases} \min\left\{2M, \frac{4}{5}(M+N), \frac{3}{2}N\right\} & 0 \leq M < \frac{25}{24}N \\ \min\left\{2N, \frac{12}{11}M + \frac{4}{11}N\right\} & M \geq \frac{25}{24}N \end{cases}$$



DoF versus the ratio between the number of antennas at BS and UE

DoF Comparison

- The achievable DoF of the cooperative system is always greater than or equal to the upper bound on the DoF of the full-duplex system.
- At M/N=1.5, the cooperative system yields at least 25% gain in DoF compared to the full-duplex system.
- Adding the full-duplex capability to the cooperative case does not yield significant gain; the maximum DoF gain cannot exceed 12:5% of the DoF of the half-duplex cooperative system



DoF versus the ratio between the number of antennas at BS and UE

Future Work

- Macro cell
  - Full duplex
  - BS employs L full-duplex separate antennas
  - Perfect self-interference cancellation

- Femto cell
  - Half-duplex (only downlink is operational)
  - M antennas at BS
  - BS transmits with low power

- All UEs are half-duplex with N antennas each

- We assume that $L \geq M \geq N$

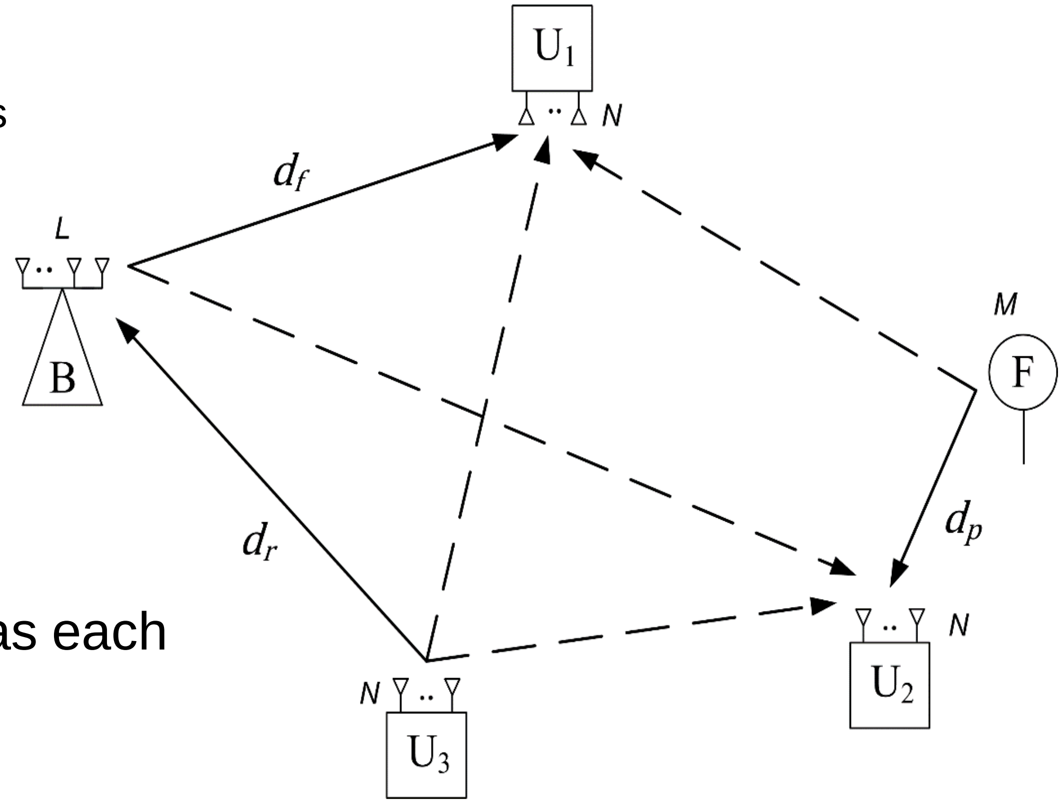


Fig. System Model

What is the optimum antenna allocation at the Macro BS and the DoF ?

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Future Work

- Full-duplex Macro BS: $d_\Sigma = \max\left\{\frac{3N}{2}, \min\left\{2N, L, \frac{M}{2} + N\right\}\right\}$
- Half-duplex system: $d_\Sigma = \min\{M, 2N\}$

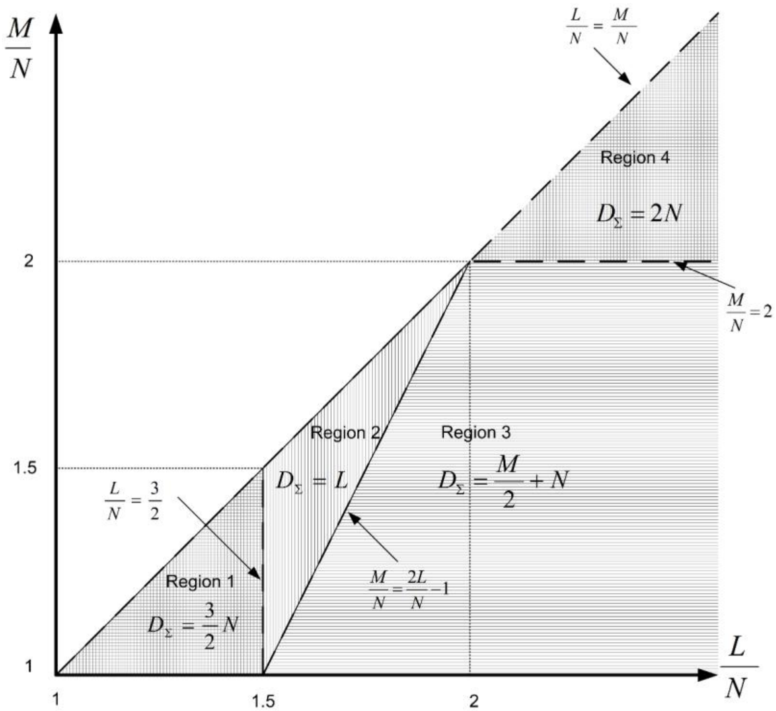

Fig. : DoF of the system

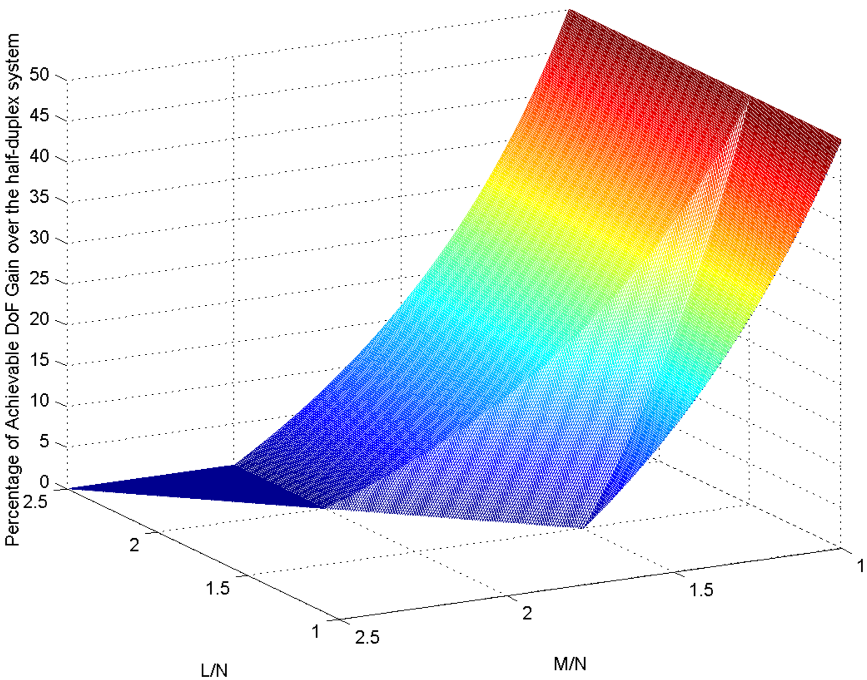

Fig. : DoF gain over half-duplex macro BS