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Interference Alignment for Heterogeneous Full-Duplex Cellular Networks

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Outline

- Introduction
- System Model
- Main Results
  - Outer bounds on the DoF
  - Optimum Antenna Allocation
  - Achievable scheme
- Conclusion

Introduction

Cellular Full-duplex Transmission

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

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

Introduction

- **Implementation**
  - Shared antenna
  - Separate antenna

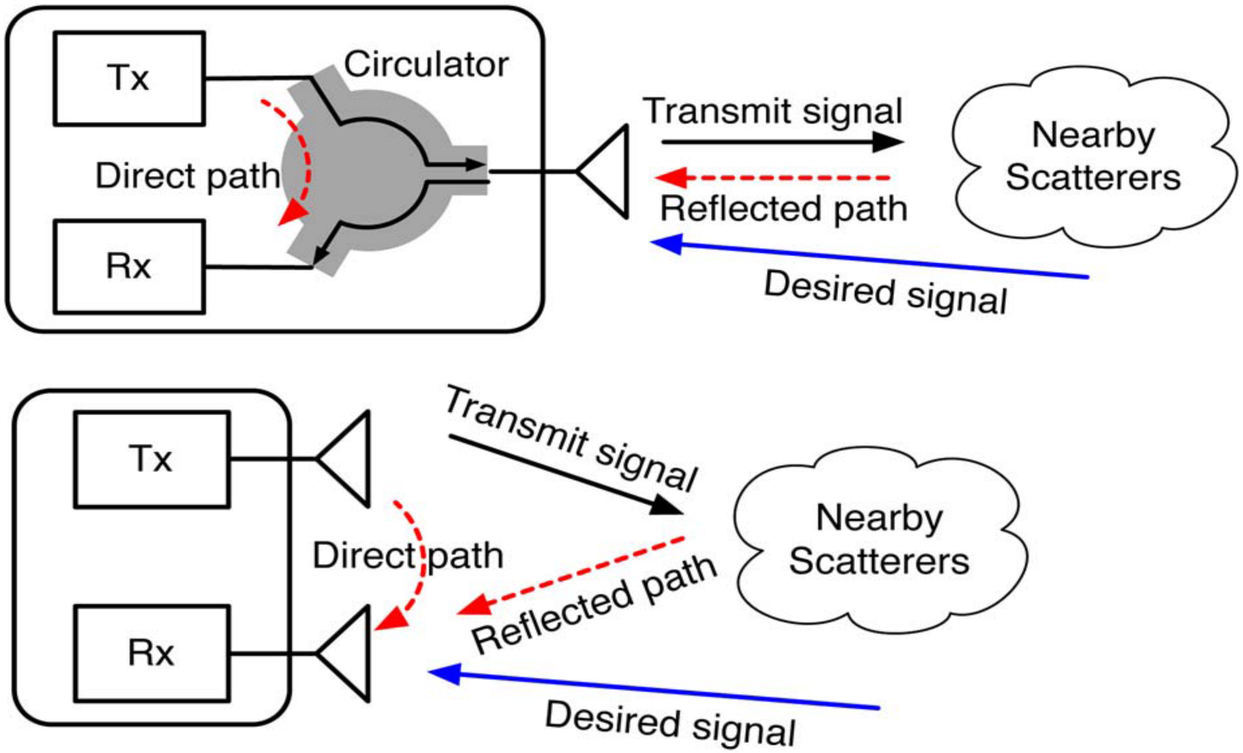


*Fig. 1: Shared- and separate -antenna full-duplex transceivers**

* 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.

System Model

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

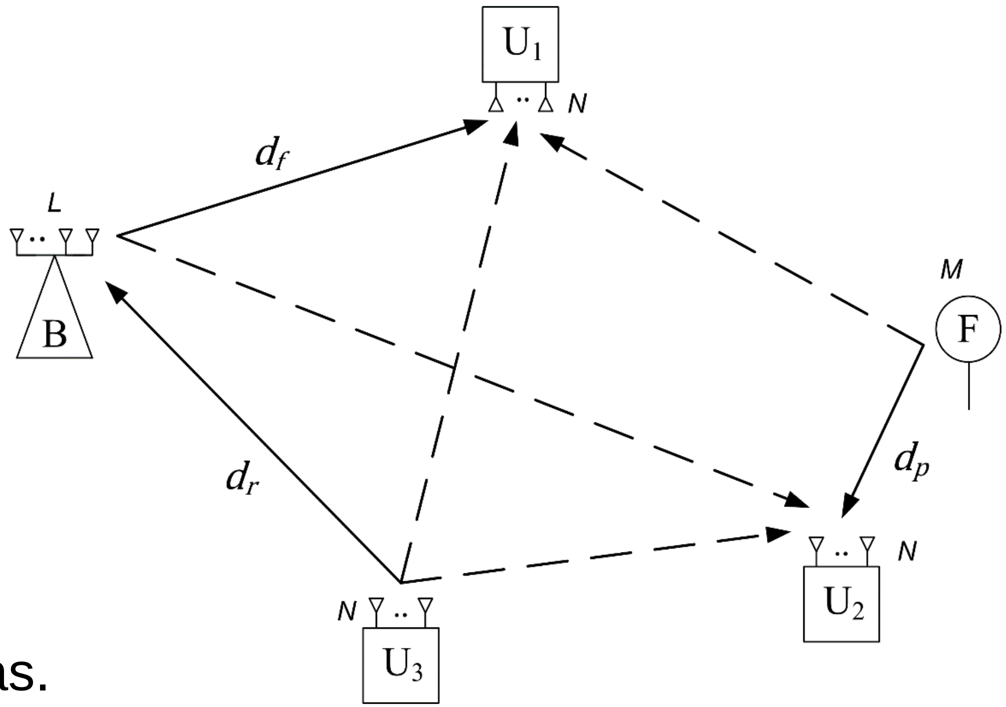


Fig. 2: System Model

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

- Each UEs is half-duplex with *N* antennas.

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

What is the optimum antenna allocation at the Macro BS ?

System Model

▪ Degrees of Freedom

- The total DoF of a network is defined as

$$d_{\Sigma} = \lim_{\mathrm{SNR}\to\infty} \frac{C(\mathrm{SNR})}{\log(1+\mathrm{SNR})}$$

- The DoF represents the rate of growth of network capacity with log the SNR.

- In most networks, the DoF represents the number of interference-free streams that can be transmitted in the network.

System Model

Earlier Work

- Earlier work on the DoF of Full duplex cellular systems considered only 1 cell.
  - [1], [2] considered a shared-antenna BS communicating with K single-antenna full-duplex MSs. The total DoF of the system can be doubled if the number of users is large enough.
  - [3], [4] considered a separate-antenna full duplex BS with M_U receive antennas and M_D transmit antennas. DoF Gain over a half-duplex system employing max{M_U;M_D} antennas. Comparison was not not fair.

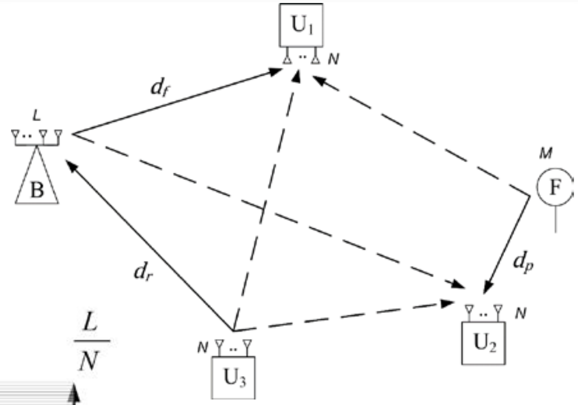
- Two-cell case considered in [5] with separate-antenna full-duplex BSs and MSs. The maximum DoF gain cannot exceed 33% compared to a half-duplex system employing the same total number of antennas.

- [1] S.H. Chae and S.H. Lim, "Degrees of freedom of cellular networks: Gain from full-duplex operation at a base station," *in Globecom*, December 2014, pp. 4048–4053.
- [2] A. Sahai, S. Diggavi, and A. Sabharwal, "On degrees-of-freedom of full-duplex uplink/downlink channel," in *ITW*, September 2013, pp. 1–5.
- [3] K. Kim, S.-W. Jeon, and D.K. Kim, "The feasibility of interference alignment for full-duplex MIMO cellular networks," *IEEE Comm. Lett*., vol. 19, pp. 1500–1503, September 2015.
- [4] S.-W. Jeon, S.H. Chae, and S.H. Lim, "Degrees of freedom of full duplex multiantenna cellular networks," in *ISIT*, June 2015, pp. 869–873.
- [5] A. El-Keyi and H. Yanikomeroglu, "Cooperative versus full-duplex communication in cellular networks: A comparison of the total degrees of freedom," in VTC, September 2016.

Main Results

- Full-duplex Macro BS:

$$d_\Sigma = \max\left\{\frac{3N}{2}, \min\left\{2N, L, \frac{M}{2} + N\right\}\right\}$$



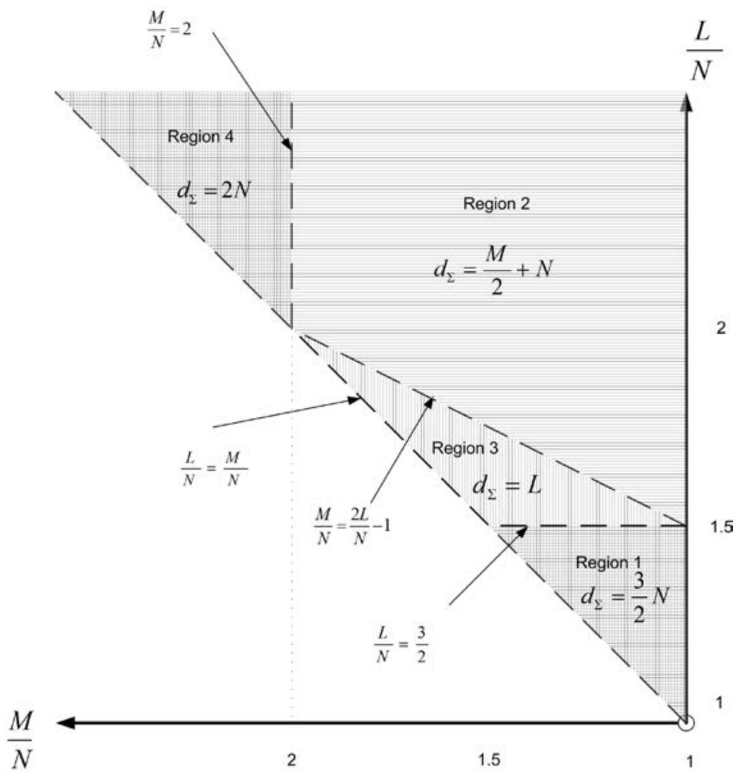
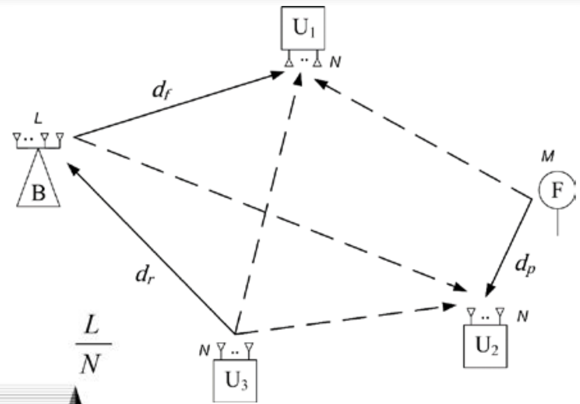


Fig. 3: DoF of the full-duplex system

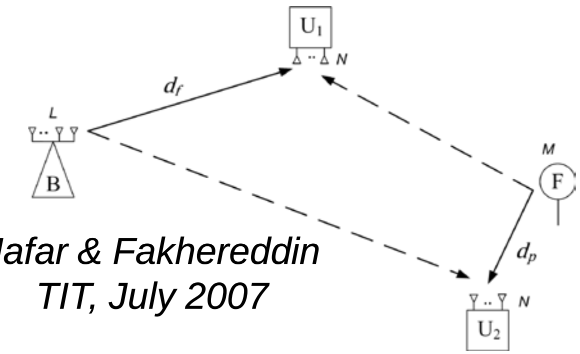
Main Results

- Full-duplex Macro BS:

$$d_\Sigma = \max\left\{\frac{3N}{2}, \min\left\{2N, L, \frac{M}{2}+N\right\}\right\}$$



- Half-duplex system: $d_\Sigma = \min\{M, 2N\}$



Jafar & Fakhereddin
TIT, July 2007

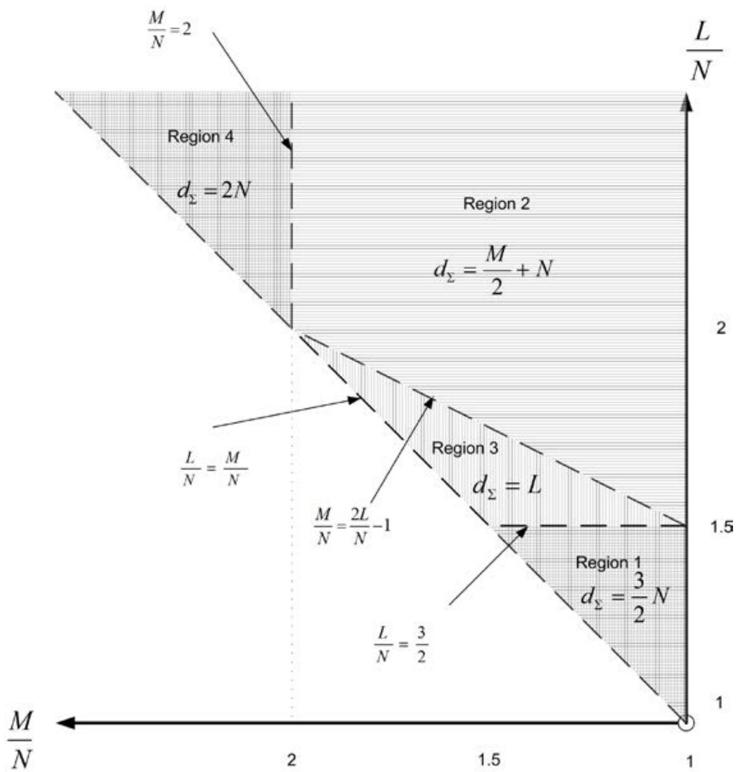


Fig. 3: System DoF with full-duplex macro-BS

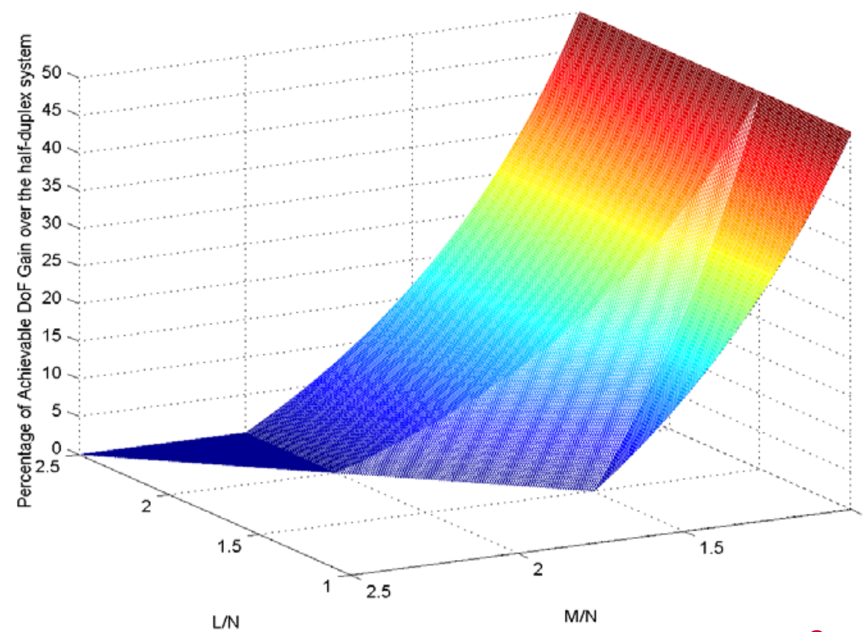
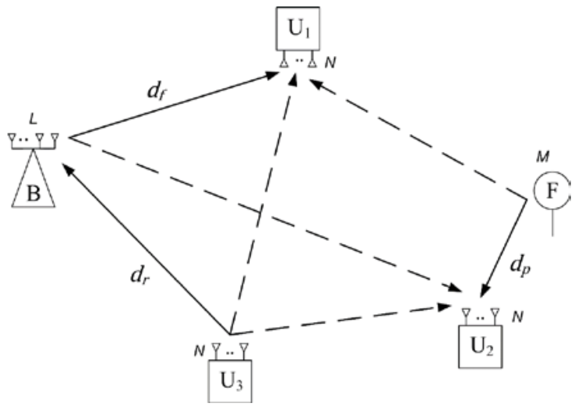


Fig. 4: System DoF gain over half-duplex macro-BS

Main Results

Outer bounds on the DoF of the system



3-user interference channel

- Partly connected
- Message feedback at macro-BS receiver
- Output feedback at macro-BS transmitter

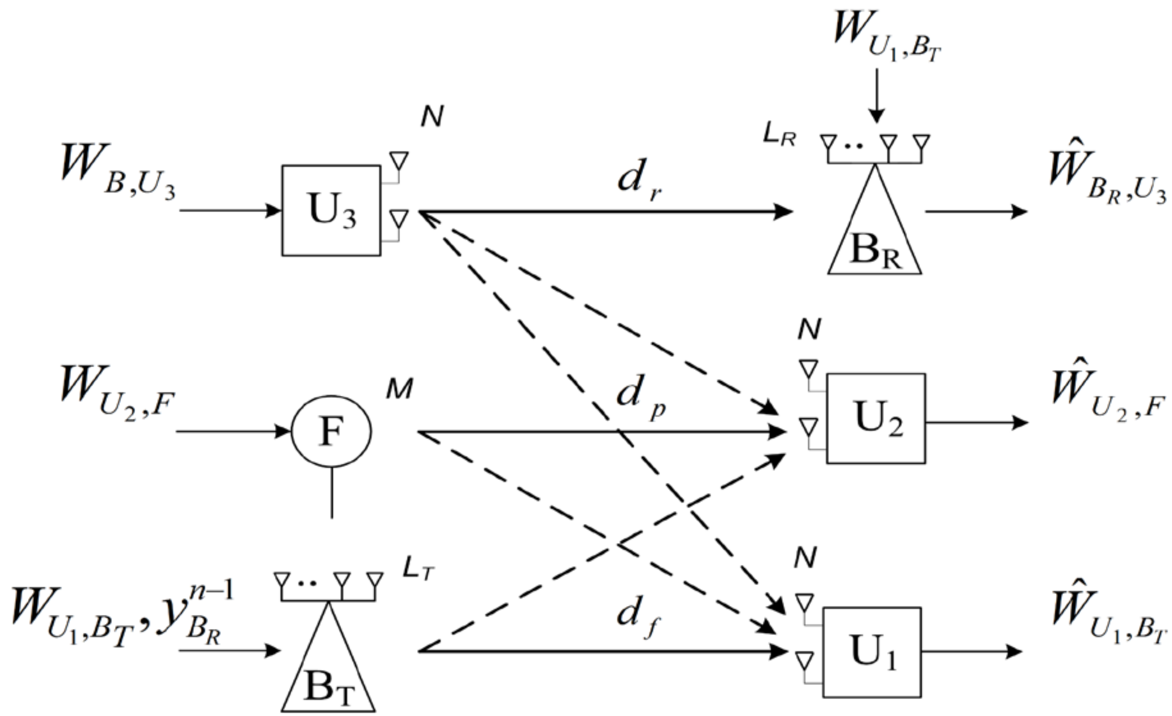


Fig. 5: Equivalent system model

Main Results

- Point-to-Point channel

$$d_r \leq L_R$$

- 2-user interference channel

$$d_f + d_p \leq \min\{2N, M, \max\{L_T, N\}\}$$

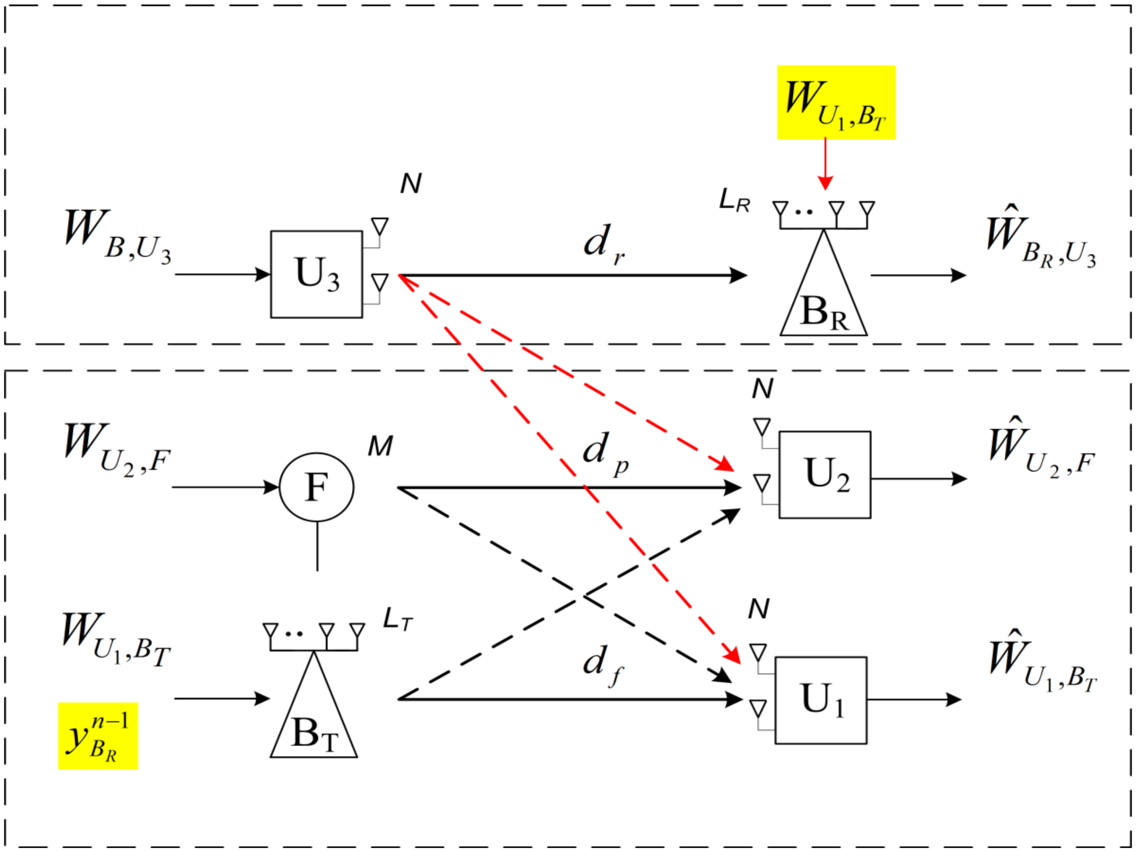
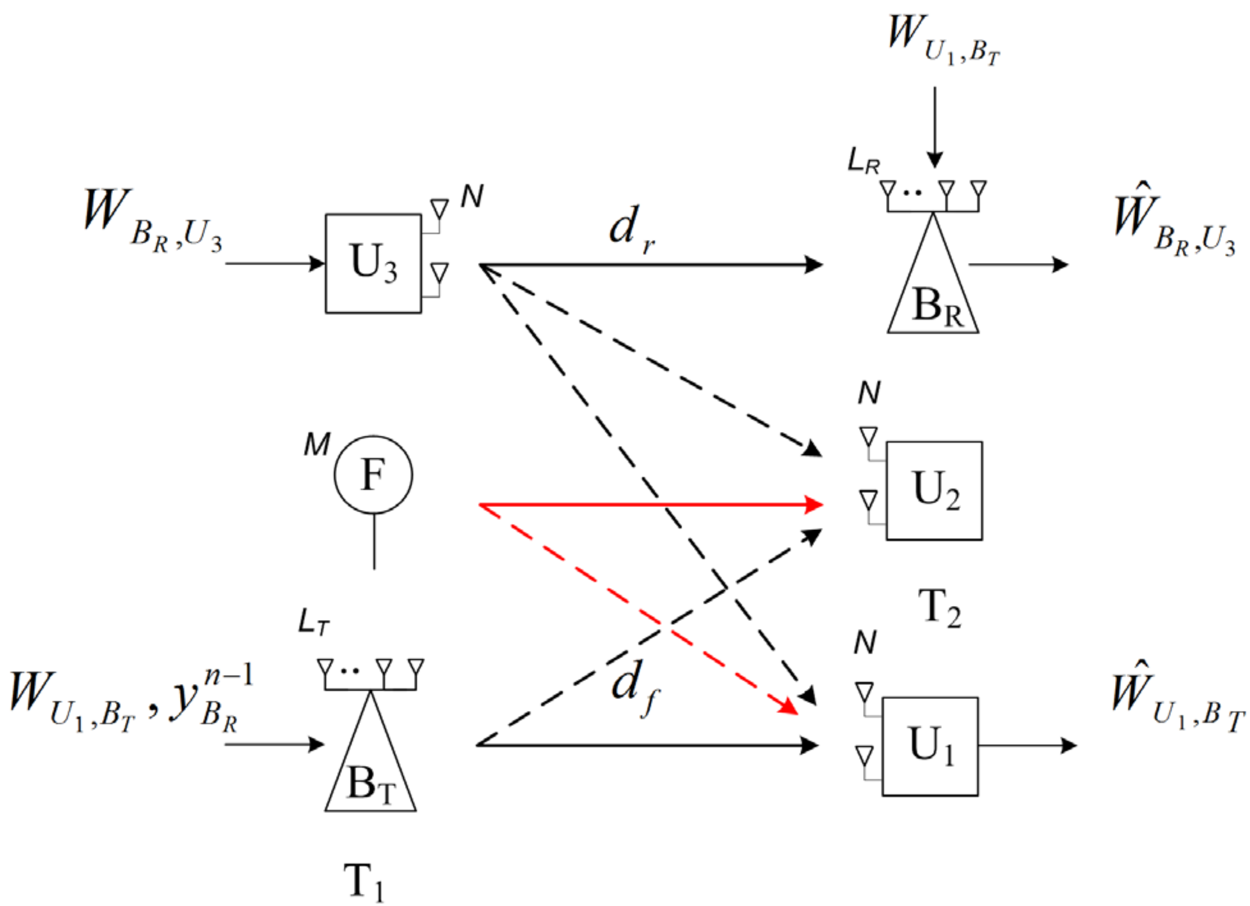


Fig. 6: Resulting system after removing interference links due to U_3

Main results

- Eliminating the message from F

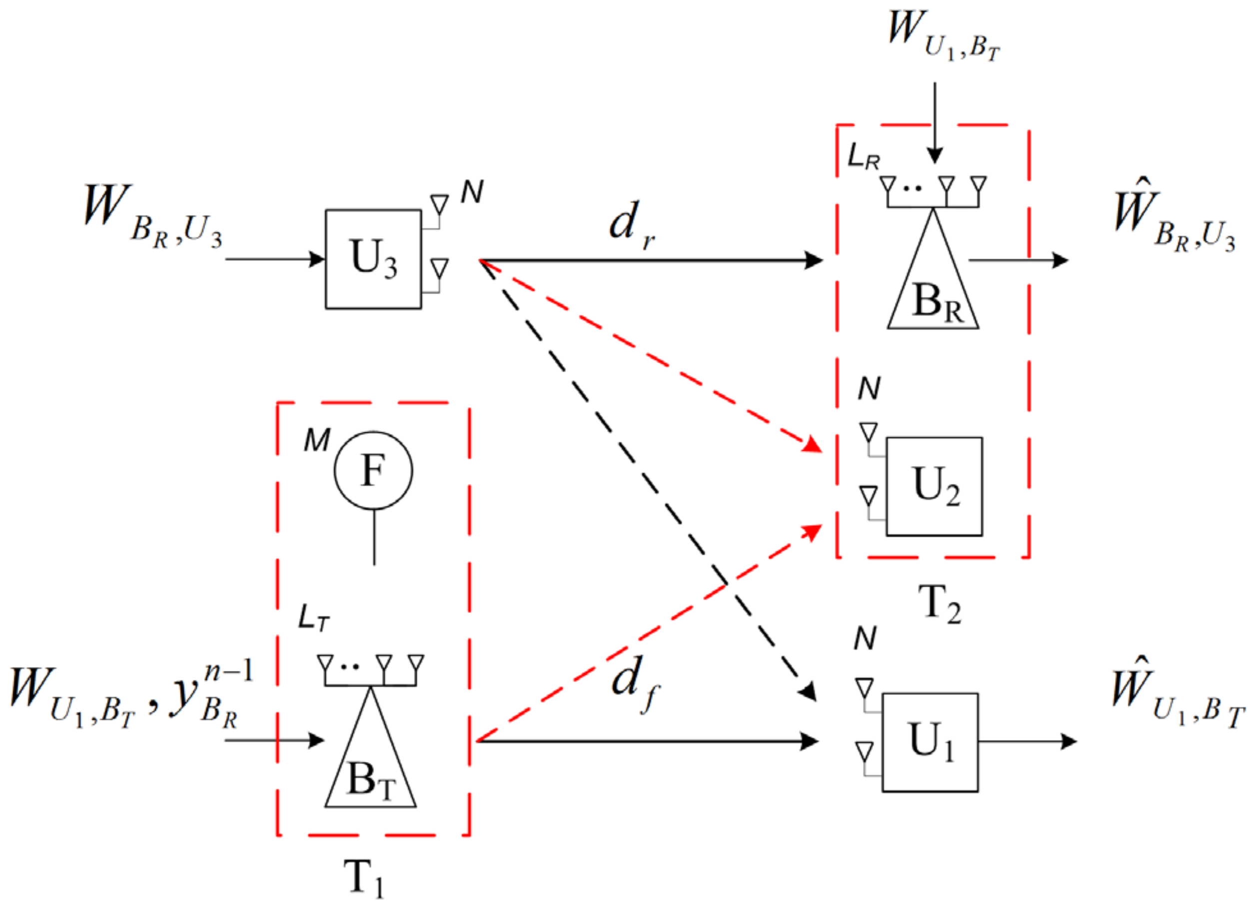


Main results

- Allowing full cooperation between:

  F & B_T

  U2 & B_R



Main results

- Resulting system is a Z channel

$$d_f + d_r \leq N$$

Jafar & Shamai
TIT, Jan 2008

Similarly, we can get

$$d_p + d_r \leq N$$

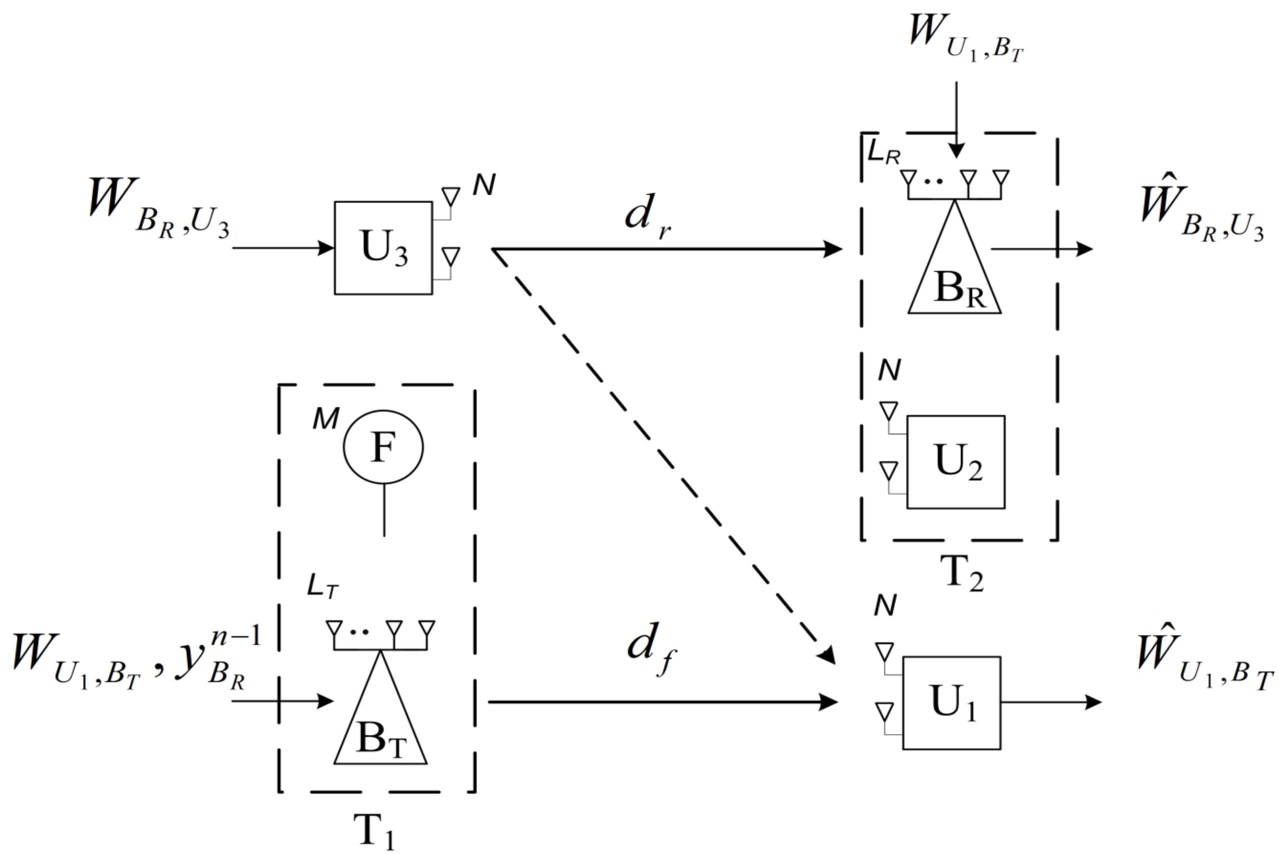


Fig. 7: Resulting system after eliminating the message from F to U_2 and cooperation between terminals

Main results

Optimal Antenna Allocation

- The optimum antenna allocation for the Macro cell is formulated as

$$\max_{L_T, d_f, d_r, d_p} \; d_f + d_r + d_p$$

subject to

$$d_f + d_p \leq \min\{2N, M, \max\{L_T, N\}\}$$
$$d_r \leq L - L_T$$
$$d_f + d_r \leq N$$
$$d_p + d_r \leq N$$
$$0 \leq L_T \leq L$$

- The problem is non-convex yet a closed-form optimum solution can be obtained by decomposing the problem into two convex subproblems.
- It can be shown that

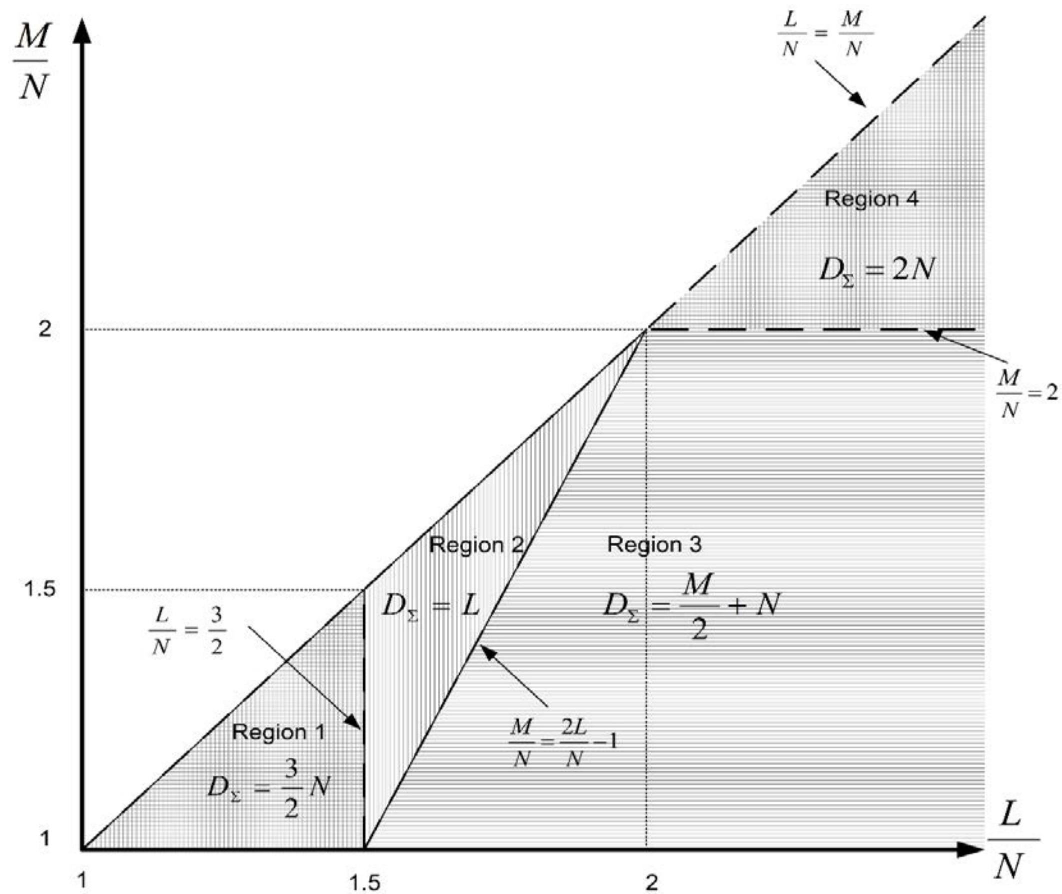
$$d_f + d_r + d_p \leq \max\left\{\frac{3N}{2}, \min\left\{2N, L, \frac{M}{2} + N\right\}\right\}$$

Main Results

Achievable scheme

- Achievable scheme depends on the relationship between *L*, *M*, and *N*.

- Four achievability schemes are proposed for Regions 1-4.



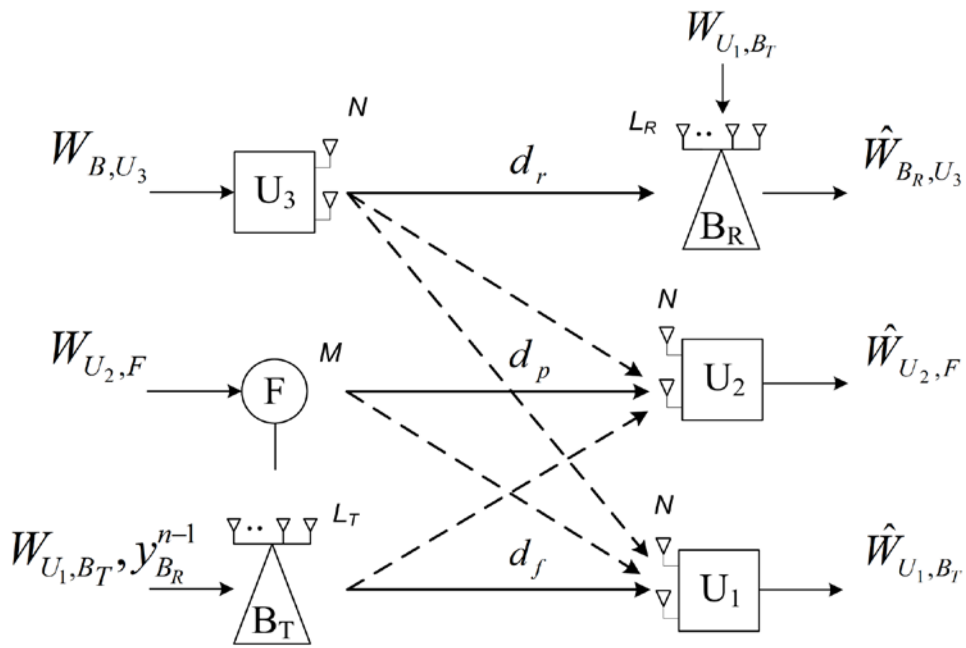
Main Results

Achievable scheme

- Achievable scheme depends on the relationship between *L*, *M*, and *N*.

- Four achievability schemes are proposed for Regions 1-4.

- Precoder design:
  - U_3 causes interference at U_1 and U_2.
  - F can transmit in nullspace of channel to U_1 or align its interference with that caused by U_3 at U_1.
  - B_T can transmit in nullspace of channel to U_2 (if $L_T > N$) or align its interference with that caused by U_3 at U_1.



Main Results

Achievable scheme

Region 1: $L \leq \frac{3N}{2}$

- Antenna allocation: $L_T = L_R = \frac{N}{2}$
- DoF allocation: $d_f = d_R = d_p = \frac{N}{2}$
- Precoder design:

$$H^{-1}_{U_2,U_3} V_{U_3} = H^{-1}_{U_2,B_T} V_{B_T}$$

$$H^{-1}_{U_1,U_3} V_{U_3} = H^{-1}_{U_1,F} V_F$$

Interference is aligned in $\frac{N}{2}$ dimensional subspace

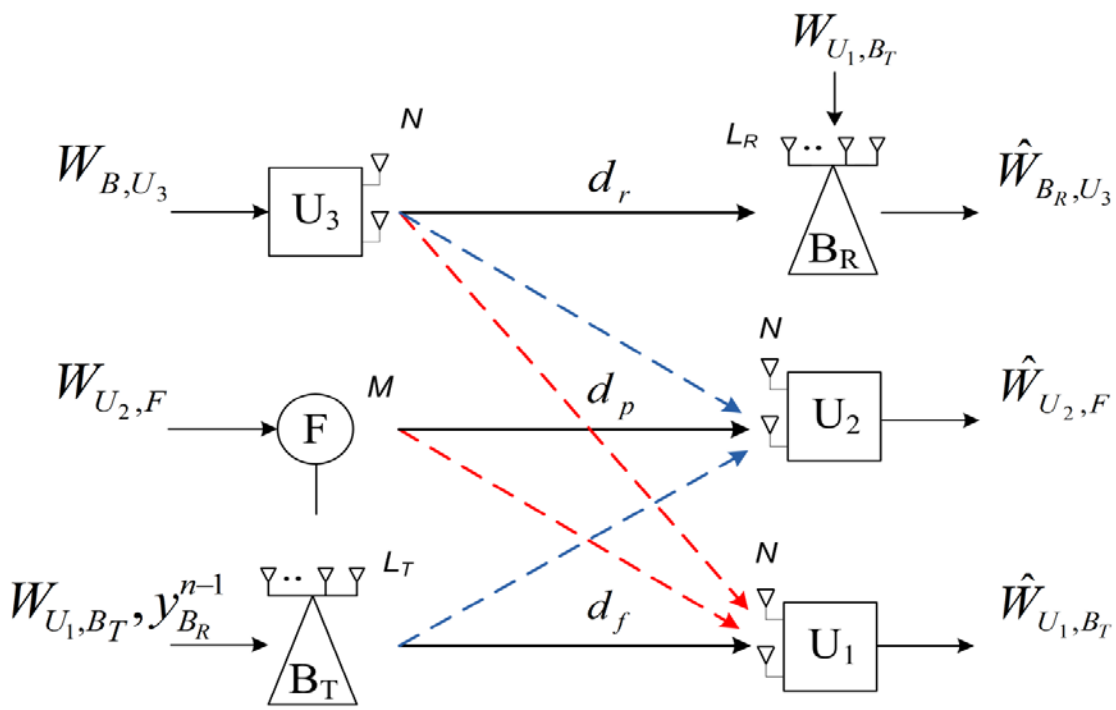


Fig. 8: Achievability through Interference alignment at U_1 and U_2

Main Results

Achievable scheme

Region 2: $L \geq \frac{M}{2} + N, M \leq 2N$

- Antenna allocation: $L_T = M, L_R = L - M$
- DoF allocation: $d_f = d_p = \frac{M}{2}, d_r = N - \frac{M}{2}$
- Precoder design: Divide the precoders of the BSs into two subprecoders

$$V_{B_T} = \left[V_{B_T}^{(1)}, V_{B_T}^{(2)} \right], \; V_F = \left[V_F^{(1)}, V_F^{(2)} \right]$$

- First subprecoder sends $N - \frac{M}{2}$ streams via interference alignment with the precoder of U_3.
- Second subprecoder directs *M-N* streams in the null-space of the non-intended UE, i.e.,

$$V_{B_T}^{(2)} = N\{H_{U_2,B_T}\}, \; V_F^{(2)} = N\{H_{U_1,F}\}$$

Main Results

Achievable scheme

Region 3: $L \le \frac{M}{2} + N, M \le 2N$

- Antenna allocation: $L_T = M, L_R = L - M$
- DoF allocation: $d_f = d_p = \frac{M}{2}, d_r = L - M$
- Precoder design: Divide the precoders of the BSs into three subprecoders

$$V_{B_T} = [V_{B_T}^{(1)}, V_{B_T}^{(2)}, V_{B_T}^{(3)}], V_F = [V_F^{(1)}, V_F^{(2)}, V_F^{(3)}]$$

- First subprecoder sends $L - M$ streams via interference alignment with the precoder of U_3.
- Second subprecoders directs *M-N* streams in the null-space of the non-intended UE.
- Third part of the precoders is selected randomly where $N - L + \frac{M}{2}$ streams are allowed to interfere on the UEs.

Main Results

Achievable scheme

Region 4: $M \geq 2N$

- Antenna allocation: $L_T = 2N, L_R = 0$
- DoF allocation: $d_f = d_p = N, d_r = 0$
- Precoder design
  - Half duplex operation of the macro-BS is optimal.
  - Each Bs transmits *N* streams and directs its transmission to the null-space of its non-intended UE

Conclusion

- We have characterized the DoF of a heterogeneous network composed of a full-duplex macro-BS and half-duplex femto-cell.
- The optimum antenna allocation for the uplink and downlink of the macro-cell was provided.
- Precoders designed using interference alignment and avoidance techniques.
- Full-duplex inband transmission at the macro-BS can increase the DoF when the number of antennas at the femto-BS is limited.
- DoF gain over half-duplex system reaches 50% when the femtocell has the same number of antennas as the UEs.