Forward Link Analysis for Full-Duplex Cellular Networks with Low Resolution ADC/DAC[1]

Elyes Balti and Brian L. Evans
6G@UT Research Center
Wireless Networking and Communications Group (WNCG)
Department of Electrical and Computer Engineering
The University of Texas at Austin, Austin, Texas, 78712
ebalti@utexas.edu, bevans@ece.utexas.edu

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Outline

Introduction

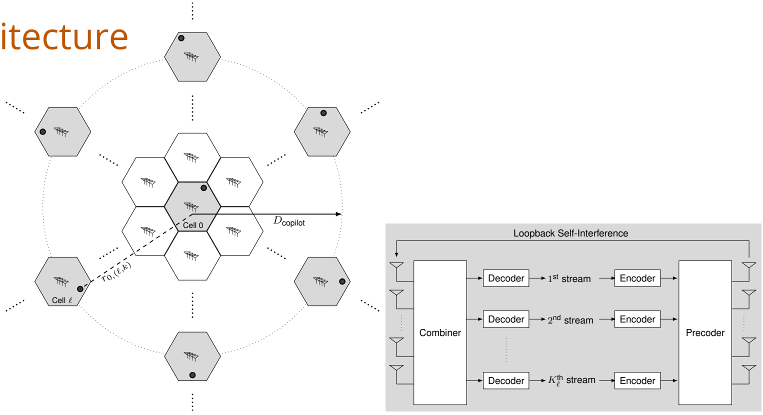
- Full duplex: transmission and reception in same time/frequency resource block
- Benefits
  - Double spectral efficiency
  - Reduce latency
  - Enhance reliability/coverage
- Challenge: Loop-back self-interference
  - Transmitted signal received by co-located receiver
  - Saturates receiver analog-to-digital converters (ADCs)
  - ADC saturation results in poor spectral efficiency
- Full duplex applications
  - Machine-to-machine communications
  - Integrated access and backhaul
- Proposed in 3GGP Release 17 cellular standard

Introduction

- Multi-antenna systems reduce hefty power consumption by reducing
  - Number of RF processing chains using hybrid analog/digital beamforming
  - Data converter resolution
- Solution for full-duplex multiantenna basestation with low-resolution converters
  - Use degrees of freedom in the all-digital beamformer design due to number of antennas to suppress self-interference
- Contributions
  - Provide unified framework for cellular forward link (downlink).
  - Derive signal to quantization plus interference plus noise ratio (sqinr).
  - Quantify effects on outage probability and spectral efficiency due to
    - Quantization error
    - Pilot contamination
    - Self interference
    - Number of users
    - Overhead

Outline

Architecture



(a) (b)

Figure: Fig. 1a Hexagonal lattice network. The cell of interest and the cells belonging to subset $\mathcal{C}$, i.e., all the ones reusing the same pilot dimensions, are shaded and a copilot user equipment in each cell is indicated by a circle. Also indicated is the distance $r_{\mathbf{0},(\ell,k)}$ between the cell of interest cell 0 and the k-th user equipment served by the cell ℓ. In addition, indicated is the distance $D_{\mathbf{copilot}}$ between the cell of interest and its first tier of copilot cells. Fig. 1b Basic abstraction of a FD BS: The uplink user equipment (UE) sends the data to the BS independently from the data intended to the downlink UE sent from the BS. Since the BS transmits and receives simultaneously at the same resource blocks, SI leakage is created in the form of a loopback from TX to RX sides of the BS.

Outline

Model

1. Network geometry: Hexagonal lattice.
2. Cellular systems (multicell and multiuser).
3. BSs and UEs operate in FD and Half-Duplex (HD), respectively.
4. Massive number of antennas $N_a \gg 1$ at the BS and UEs are equipped with a single antenna.
5. BSs operate in low-resolution ADC/DAC.
6. Additive Quantization Noise Model (AQNM): $\mathbf{y_q} = \alpha \mathbf{y} + \mathbf{q}$.
7. Large-scale fading: Pathloss and Lognormal shadowing.
8. Small-scale fading: Rayleigh.
9. Matched filter precoder at the BS.
10. Pilot contamination: pilots reuse per cell.
11. Channel hardening.

Outline

Signal

- From the reverse link pilots transmitted by its users, the ℓ-th BS gathers channel estimates $\hat{\boldsymbol{h}}_{\ell,(\ell,0)}, \ldots, \hat{\boldsymbol{h}}_{\ell,(\ell,K_\ell^d-1)}$. With matched filter transmitter, the precoders at cell ℓ are given by

$$\boldsymbol{f}_{\ell,k}^{\mathrm{MF}} = \sqrt{N_\mathrm{a}}\frac{\hat{\boldsymbol{h}}_{\ell,(\ell,k)}}{\sqrt{\mathbb{E}\left[\left\|\hat{\boldsymbol{h}}_{\ell,(\ell,k)}\right\|^2\right]}}, \quad k = 0, \ldots, K_\ell^d - 1$$

- The BS applies the matched filter precoder ($\boldsymbol{f}_k$) to point the signal toward the k-th downlink UE as

$$y_{q,k} = \underbrace{\alpha\sqrt{\frac{G_kP_k}{N_\mathrm{a}}}\mathbb{E}[\boldsymbol{h}_k^*\boldsymbol{f}_k]s_k}_{\text{DesiredSignal}} + \underbrace{\alpha\sqrt{\frac{G_kP_k}{N_\mathrm{a}}}\left(\boldsymbol{h}_k^*\boldsymbol{f}_k - \mathbb{E}[\boldsymbol{h}_k^*\boldsymbol{f}_k]\right)s_k}_{\text{Channel Estimation Error (Self-Interference)}} + \underbrace{\alpha\sum_{\mathrm{k}\neq k}\sqrt{\frac{G_\mathrm{k}P_\mathrm{k}}{N_\mathrm{a}}}\boldsymbol{h}_k^*\boldsymbol{f}_\mathrm{k}s_\mathrm{k}}_{\text{Intra-Cell Interference}} + \underbrace{\sum_{\ell}\sum_{\mathrm{k}=0}^{K_\ell^d-1}\sqrt{\frac{G_{\ell,\mathrm{k}}P_{\ell,\mathrm{k}}}{N_\mathrm{a}}}\boldsymbol{h}_{\ell,k}^*\boldsymbol{q}_\ell}_{\text{Aggregate AQNM}}$$

$$+ \underbrace{\alpha\sum_{\ell\neq 0}\sum_{\mathrm{k}=0}^{K_\ell^d-1}\sqrt{\frac{G_{\ell,k}P_{\ell,\mathrm{k}}}{N_\mathrm{a}}}\boldsymbol{h}_{\ell,k}^*\boldsymbol{f}_{\ell,\mathrm{k}}s_{\ell,\mathrm{k}}}_{\text{Inter-Cell Interference}} + \underbrace{\sum_{\mathrm{k}\neq k}\sqrt{T_{\mathrm{k},k}P_{\ell,\mathrm{k}}}g_{\mathrm{k},k}s_{\mathrm{k},u}}_{\text{Same Cell Inter-User Interference}} + \underbrace{\sum_{\ell\neq 0}\sum_{\mathrm{k}=0}^{K_\ell^u-1}\sqrt{T_{(\ell,\mathrm{k}),k}P_{\ell,\mathrm{k}}}g_{(\ell,\mathrm{k}),k}s_{\ell,\mathrm{k},u}}_{\text{Other Cells Inter-User Interference}} + \underbrace{v_k}_{\text{Noise}}$$

Outline

SQINR

Corollary

The matched filter precoder $\boldsymbol{f}_k^{\mathsf{MF}}$ has the following properties:

1. $\mathbb{E}\left[\|\boldsymbol{f}_k^{\mathsf{MF}}\|^2\right] = N_{\mathsf{a}}$.
2. $\mathbb{E}\left[\|\boldsymbol{f}_k^{\mathsf{MF}}\|^4\right] = N_{\mathsf{a}}^2 + N_{\mathsf{a}}$.
3. $\mathbb{E}\left[\left|\boldsymbol{h}_{\ell,k}^{*}\boldsymbol{f}_k^{\mathsf{MF}}\right|^2\right] = N_{\mathsf{a}}$.

Theorem

The output SQINR of the k-th user is given by the following equation.

$$\overline{\mathsf{sqinr}}_k^{\mathsf{MF}} = \frac{\alpha^2 \frac{N_{\mathsf{a}}}{\varrho + \frac{P_k}{P_u}\mathsf{SNR}_k^d + \sum_{\ell\in\mathcal{C}} \frac{P_{\ell,k}}{P_u}\mathsf{SNR}_{\ell,k}^d} \frac{P_k}{P_u}\frac{P_k}{P_d}\left(\mathsf{SNR}_k^d\right)^2}{\overline{\mathsf{den}}^{\mathsf{MF}}} \quad (11)$$

where $\varrho = \mathsf{SNR}_{\ell,(l,k)}^d / \mathsf{SNR}_{\ell,(l,k)}^u$ *for any ℓ, l and k as the forward-reverse SNR ratio.*

$$\overline{\mathsf{den}}^{\mathsf{MF}} = 1 + \alpha^2 \sum_{\ell} \mathsf{SNR}_{\ell,k}^d + \alpha^2 \sum_{\ell\in\mathcal{C}} \frac{N_{\mathsf{a}}}{\varrho + \frac{P_k}{P_u}\mathsf{SNR}_{\ell,k}^d + \sum_{l\in\mathcal{C}} \frac{P_{l,k}}{P_u}\mathsf{SNR}_{\ell,(l,k)}^d} \frac{P_k}{P_u}\frac{P_{\ell,k}}{P_d}\left(\mathsf{SNR}_{\ell,k}^d\right)^2$$
$$+ \sum_{\ell}\sum_{\mathrm{k}=0}^{K_\ell^u-1} \frac{P_{\ell,\mathrm{k}}}{P_u}\mathsf{SNR}_{(\ell,\mathrm{k}),k}^{\mathrm{iui}} + \alpha(1-\alpha)\sum_{\ell}\frac{P_{\ell,k}}{P_d}\mathsf{SNR}_{\ell,k}^d\left(K_\ell^d + 1\right)$$

Outline

Special Cases

Corollary

To further characterize the spectral efficiency, we derive a new bound using the following formula. Assuming statistical independence between x and y, we have

$$\mathbb{E}\left[\log\left(1+\frac{x}{y}\right)\right] \cong \log\left(1+\frac{\mathbb{E}[x]}{\mathbb{E}[y]}\right)$$

Proposition

Considering a single-cell multiuser system (without any inter-cell interference) with perfect CSI, Corollary (above) entails the results for forward link in[a].

[a] Jianxin Dai, Juan Liu, Jiangzhou Wang, Junxi Zhao, Chonghu Cheng, and Jin-Yuan Wang. Achievable Rates for Full-Duplex Massive MIMO Systems With Low-Resolution ADCs/DACs. In: *IEEE Access* 7 (2019), pp. 24343–24353. DOI: 10.1109/ACCESS.2019.2900273.

Special Cases

Proposition

With channel hardening, without full-duplexing (no inter-user interference), with full-resolution and matched filter precoder, the output SINR of the k-th downlink user is given by the following equation.

$$\overline{\mathsf{sinr}}_k^{\mathsf{MF}} = \frac{\frac{N_a}{\varrho + \frac{P_k}{P_u}\mathsf{SNR}_k^d + \sum_{\ell \in \mathcal{C}} \frac{P_{\ell,k}}{P_u}\mathsf{SNR}_{\ell,k}^d} \frac{P_k}{P_u}\frac{P_k}{P_d}\left(\mathsf{SNR}_k^d\right)^2}{1 + \sum_\ell \mathsf{SNR}_{\ell,k}^d + \sum_{\ell \in \mathcal{C}} \frac{N_a}{\varrho + \frac{P_k}{P_u}\mathsf{SNR}_{\ell,k}^d + \sum_{l \in \mathcal{C}} \frac{P_{l,k}}{P_u}\mathsf{SNR}_{\ell,(l,k)}^d} \frac{P_k}{P_u}\frac{P_{\ell,k}}{P_d}\left(\mathsf{SNR}_{\ell,k}^d\right)^2}$$

Remark

Note that this Proposition entails the same result for forward link derived in[a].

[a] Geordie George, Angel Lozano, and Martin Haenggi. Massive MIMO Forward Link Analysis for Cellular Networks. In: *IEEE Transactions on Wireless Communications* 18.6 (June 2019), pp. 2964–2976. ISSN: 1558-2248. DOI: `10.1109/twc.2019.2907584`.

Special Cases

Lemma

Neglecting the pilot contamination, the output SINR of the k-th downlink user can be reduced to

$$\overline{\text{sinr}}_k^{\text{MF}} \approx \frac{\frac{P_k}{P_u}\frac{P_k}{P_d}\left(\text{SNR}_k^d\right)^2 N_a}{\left(\varrho + \frac{P_k}{P_u}\text{SNR}_k^d\right)\left(1 + \sum_\ell \text{SNR}_{\ell,k}^d\right)}$$

Outline

Performance Measures

- The effective spectral efficiency of the k-th downlink UE is given by

$$\frac{\mathcal{I}_k^{\mathsf{eff}}}{B} = \left(1 - \beta \frac{N_{\mathsf{p}}}{N_{\mathsf{c}}}\right) \log\left(1 + \overline{\mathsf{sqinr}}_k\right), \ k = 0, \ldots, K-1$$

  where N_{p}, N_{c}, $\beta \in [0, 1]$ and B are number of pilots, number of coherence tiles, fraction of pilot overhead and bandwidth, respectively.
- Once a transmission strategy is specified, the corresponding cumulative distribution function (CDF) or outage probability for rate R (bit/s/Hz) is then

$$P_{\mathsf{out}}(\mathsf{SNR}, R) = \mathbb{P}[\mathcal{I}(\mathsf{SNR}) < R]. \quad (1)$$

Outline

Numerical Results

Table: System Parameters.

Parameter	Value
Bandwidth	20 MHz
Pathloss Exponent (η)	2.5
Shadowing ($\sigma_{\mathbf{dB}}$)	8 dB
Downlink Transmit Power	40 W
Uplink Transmit Power	200 mW
Thermal Noise Spectral Density	-174 dBm/Hz
Noise Figure	3 dB
BS Antennas Gain	12 dB
Number of Antennas ($N_{\mathbf{a}}$)	100
Uplink/Downlink Users per Cell (K_ℓ)	10
Number of Pilots per Cell ($N_{\mathbf{p}}$)	$3K_\ell$
Fraction of Pilot Overhead (β)	0.5
Fading Coherence Tile ($N_{\mathbf{c}}$)	20,000 (Pedestrians)
ADC/DAC resolution	3 bits

Robert W. Heath Jr. and Angel Lozano. *Foundations of MIMO Communication*. Cambridge University Press, 2018. DOI: 10.1017/9781139049276; George, Lozano, and Haenggi 2019.

CDF

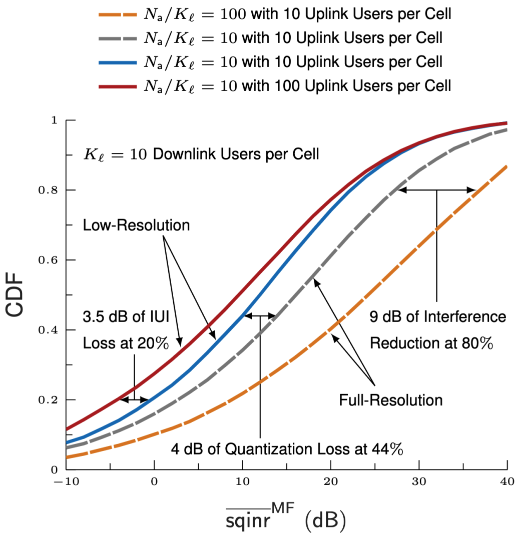


Figure: Forward link results: Effects of full-duplexing, ADC/DAC quantization error, and the factor N_a / K_ℓ on the CDF of the SQINR. The dashed gray and solid blue curves are simulated for full and low resolution DAC, respectively.

Effective Spectral Efficiency

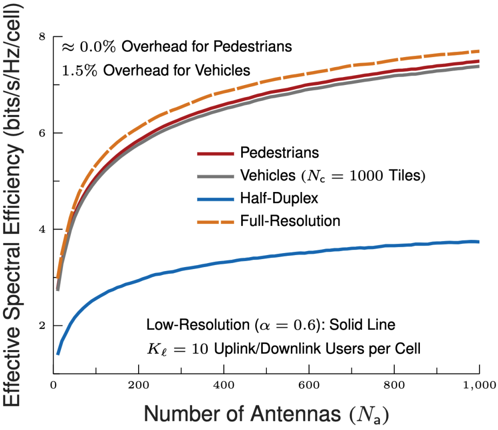


Figure: Forward link results: Effects of SI power, overhead, DAC resolution, duplexing mode and pilot contamination on the spectral efficiency. Dashed yellow curve stands for full-resolution, pedestrians and full-duplex. Solid red and gray curves stand for low-resolution full-duplex. Solid blue curve stands for low-resolution DAC, half-duplex and pedestrians scenario.

Conclusion

- Considered full-duplex multiantenna basestations
  - All-digital beamformers
  - Low-resolution data converters
  - Arranged on hexagonal lattice
- Developed a unified framework for forward link analysis
  - Derived outage probability and spectral efficiency based on received signal, interference, quantization error, and thermal noise
  - Derived special cases
- Designed digital beamformers
  - Used degrees of freedom due to massive number of antennas
  - Compensated quantization error and inter-user interference
- Full duplex system outperforms half-duplex mode in effective spectral efficiency
  - Gives evidence of feasibility of full-duplex cellular networks

Thanks for your attention
Questions ?

The University of Texas at Austin
Cockrell School of Engineering