Full-Duplex Massive MIMO Systems with Low Resolution Data Converters[1]

Application on Cellular Networks

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

[1] This work was supported by AT&T Labs and NVIDIA, affiliates of the 6G@UT Research Center within the Wireless Networking and Communications Group at The University of Texas at Austin.

Outline I

Outline II

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 and inter-user 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 3GPP 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 interference
- Contributions
  - Provide unified framework for cellular reverse and forward links
  - Derive signal to quantization plus interference plus noise ratio (**sqinr**)
  - Quantify effects on outage probability and spectral efficiency due to
    - Quantization error
    - Self-interference
    - Inter-user interference
    - Number of users

Outline I

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

Description

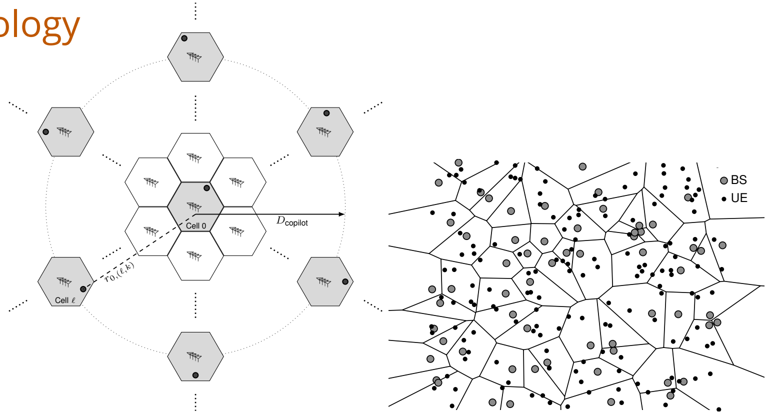
1. Network topology: Hexagonal and PPP tessellation.
2. Cellular systems (multicell and multiuser).
3. BSs and UEs operate in FD and Half-Duplex (HD), respectively.
4. Massive number of antennas $N_a \gg 1$ at the BS and UEs are equipped with a single antenna.
5. BSs operate in low-resolution ADC/DAC.
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/receiver at the BS.
10. Channel hardening.

Outline I

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

Topology



(a) (b)

Figure 1: 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 illustrates the PPP Voronoi tessellation.

Outline I

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

Architecture

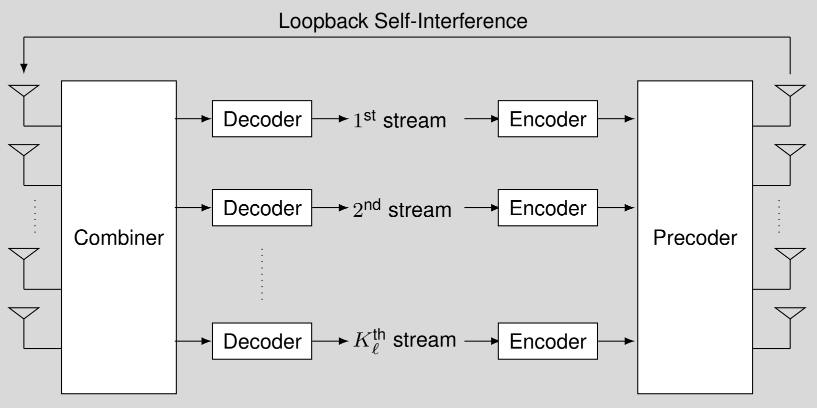


Figure 2: Full-duplex BS. Uplink UE sends data to the BS independently from the data intended for the downlink UE sent from the BS. Since the BS transmits and receives at the same time and on the same resource blocks, SI leakage creates loopback interference from the TX to the RX side of the BS.

Outline I

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

Model

- Large-Scale Fading: Pathloss and Lognormal Shadowing.

$$G_{\ell,(l,k)} = \frac{L_{\text{ref}}}{r_{\ell,(l,k)}^{\eta}} \chi_{\ell,(l,k)} \quad (1)$$

- Small-Scale Fading: Rayleigh.
- Low-resolution data converters and AQNM.

$$\mathbf{y_q} = \alpha \mathbf{y} + \mathbf{q} \quad (2)$$

- For $b \leq 5$, $\rho = 1 - \alpha$ values is given by Table 1.

Table 1: ρ for different values of b.

b	1	2	3	4	5
ρ	0.3634	0.1175	0.03454	0.009497	0.002499

- Otherwise, ρ can be approximated by

$$\rho \approx \frac{\pi\sqrt{3}}{2} \cdot 2^{-2b} \quad (3)$$

- ρ is the inverse of the signal-to-quantization noise ratio

Li Fan, Shi Jin, Chao-Kai Wen, and Haixia Zhang. Uplink Achievable Rate for Massive MIMO Systems With Low-Resolution ADC. In: *IEEE Commun. Let.* 19.12 (2015), pp. 2186–2189. DOI: 10.1109/LCOMM.2015.2494600.

Outline I

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

Signal Model

- The received signal of the k-th uplink user at the BS is given by

$$y^u_{q,k} = \underbrace{\alpha_u \sqrt{G_k P_k}\mathbb{E}[\boldsymbol{w}_k^* \boldsymbol{h}_k] s_k}_{\text{Desired Signal}} + \underbrace{\alpha_u \sum_{\mathrm{k} \neq k} \sqrt{G_\mathrm{k} P_\mathrm{k}} \boldsymbol{w}_k^* \boldsymbol{h}_\mathrm{k} s_\mathrm{k}}_{\text{Intra-Cell Interference}} + \underbrace{\alpha_u \boldsymbol{w}_k^* \boldsymbol{v}}_{\text{Filtered Noise}}$$

$$\overbrace{+ \underbrace{\alpha_u \sqrt{G_k P_k} \left(\boldsymbol{w}_k^* \boldsymbol{h}_k - \mathbb{E}[\boldsymbol{w}_k^* \boldsymbol{h}_k]\right) s_k}_{\text{Channel Estimation Error}} + \underbrace{\alpha_u \alpha_d \sqrt{P_\mathrm{SI}} \sum_{\mathrm{k}=0}^{K^d - 1} \boldsymbol{w}_k^* \boldsymbol{H}_\mathrm{SI} \boldsymbol{f}_\mathrm{k} s^d_\mathrm{k}}_{\text{Self-Interference due to Full-Duplexing}}}^{\text{Aggregate Self-Interference}} + \quad (4)$$

$$\underbrace{\alpha_u \sqrt{P_\mathrm{SI}} \boldsymbol{w}_k^* \boldsymbol{H}_\mathrm{SI} \boldsymbol{q}_d + \boldsymbol{w}_k^* \boldsymbol{q}_u}_{\text{Aggregate AQNM}} + \underbrace{\alpha_u \sum_{\ell \neq 0} \sum_{\mathrm{k}=0}^{K^u_\ell - 1} \sqrt{G_{\ell,\mathrm{k}} P_{\ell,\mathrm{k}}} \boldsymbol{w}_k^* \boldsymbol{h}_{\ell,\mathrm{k}} s_{\ell,\mathrm{k}}}_{\text{Inter-Cell Interference}}$$

- The matched filter receiver $\boldsymbol{w}_k^{\mathrm{MF}}$ satisfies the following properties:
  1. $\mathbb{E}\left[\|\boldsymbol{w}_k^{\mathrm{MF}}\|^2\right] = N_\mathrm{a}$.
  2. $\mathbb{E}\left[\|\boldsymbol{w}_k^{\mathrm{MF}}\|^4\right] = N_\mathrm{a}^2 + N_\mathrm{a}$.
  3. $\mathbb{E}\left[\left|\boldsymbol{w}_k^{\mathrm{MF}*} \boldsymbol{h}_{\ell,\mathrm{k}}\right|^2\right] = N_\mathrm{a}$.

Outline I

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

Uplink SQINR

Theorem

The output SQINR of the k-th uplink user is given by

$$\overline{\text{sqinr}}_k^{\text{MF}} = \frac{\alpha_u^2 G_k P_k \left|\mathbb{E}[\boldsymbol{w}_k^{\text{MF}*}\boldsymbol{h}_k]\right|^2}{\overline{\text{den}}_u^{\text{MF}}} \qquad (5)$$

where $\overline{\text{den}}_u^{\text{MF}}$ *is given by*

$$\overline{\text{den}}_u^{\text{MF}} = \alpha_u^2 G_k P_k \, var[\boldsymbol{w}_k^{\text{MF}*}\boldsymbol{h}_k] + \alpha_u^2 \sum_{k \neq k} G_k P_k \mathbb{E}\left[\left|\boldsymbol{w}_k^{\text{MF}*}\boldsymbol{h}_k\right|^2\right] + \alpha_u^2 \sigma^2 \mathbb{E}\left[\left\|\boldsymbol{w}_k^{\text{MF}}\right\|^2\right]$$
$$+ \alpha_u^2 \sum_{\ell \neq 0} \sum_{k=0}^{K_\ell^d - 1} G_{\ell,k} P_{\ell,k} \mathbb{E}\left[\left|\boldsymbol{w}_k^{\text{MF}*}\boldsymbol{h}_{\ell,k}\right|^2\right] + \alpha_u^2 \alpha_d^2 P_{\text{SI}} \sum_{k=0}^{K^d - 1} \mathbb{E}\left[\left|\boldsymbol{w}_k^{\text{MF}*}\boldsymbol{H}_{\text{SI}}\boldsymbol{f}_k^{\text{MF}}\right|^2\right]$$
$$+ \alpha_u^2 P_{\text{SI}} \mathbb{E}\left[\left|\boldsymbol{w}_k^{\text{MF}*}\boldsymbol{H}_{\text{SI}}\boldsymbol{q}_d\right|^2\right] + \mathbb{E}\left[\left|\boldsymbol{w}_k^{\text{MF}*}\boldsymbol{q}_u\right|^2\right] \qquad (6)$$

Outline I

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

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 reverse 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.

Outline I

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws

- System Performances
  - Performance Measures
  - Numerical Results

- Conclusion

Signal Model

- The received signal of the k-th downlink user is given by

$$\begin{aligned}
y^d_{q,k} = & \underbrace{\alpha_d \sqrt{\frac{G_k P_k}{N_a}} \mathbb{E}[\boldsymbol{h}_k^* \boldsymbol{f}_k] s_k}_{\text{Desired Signal}} + \underbrace{\alpha_d \sqrt{\frac{G_k P_k}{N_a}} \left(\boldsymbol{h}_k^* \boldsymbol{f}_k - \mathbb{E}[\boldsymbol{h}_k^* \boldsymbol{f}_k]\right) s_k}_{\text{Channel Estimation Error (Self-Interference)}} \\
& + \underbrace{\alpha_d \sum_{\mathrm{k} \neq k} \sqrt{\frac{G_k P_{\mathrm{k}}}{N_a}} \boldsymbol{h}_k^* \boldsymbol{f}_{\mathrm{k}} s_{\mathrm{k}}}_{\text{Intra-Cell Interference}} + \underbrace{\sum_{\ell} \sum_{\mathrm{k}=0}^{K^d_\ell - 1} \sqrt{\frac{G_{\ell,k} P_{\ell,\mathrm{k}}}{N_a}} \boldsymbol{h}_{\ell,k}^* \boldsymbol{q}_\ell}_{\text{Aggregate AQNM}} + \underbrace{\sum_{\mathrm{k} \neq k} \sqrt{T_{\mathrm{k},k} P^u_{\ell,\mathrm{k}}} \boldsymbol{g}_{\mathrm{k},k} s_{\mathrm{k},u}}_{\text{Same Cell Inter-User Interference}} \\
& + \underbrace{\alpha_d \sum_{\ell \neq 0} \sum_{\mathrm{k}=0}^{K^d_\ell - 1} \sqrt{\frac{G_{\ell,k} P_{\ell,\mathrm{k}}}{N_a}} \boldsymbol{h}_{\ell,k}^* \boldsymbol{f}_{\ell,\mathrm{k}} s_{\ell,\mathrm{k}}}_{\text{Inter-Cell Interference}} + \underbrace{\sum_{\ell \neq 0} \sum_{\mathrm{k}=0}^{K^u_\ell - 1} \sqrt{T_{(\ell,\mathrm{k}),k} P^u_{\ell,\mathrm{k}}} \boldsymbol{g}_{(\ell,\mathrm{k}),k} s_{\ell,\mathrm{k},u}}_{\text{Other Cells Inter-User Interference}} + \underbrace{v_k}_{\text{Noise}}
\end{aligned} \quad (7)$$

- The matched filter precoder $\boldsymbol{f}_k^{\mathrm{MF}}$ satisfies the following properties:
  1. $\mathbb{E}\left[\|\boldsymbol{f}_k^{\mathrm{MF}}\|^2\right] = N_a$.
  2. $\mathbb{E}\left[\|\boldsymbol{f}_k^{\mathrm{MF}}\|^4\right] = N_a^2 + N_a$.
  3. $\mathbb{E}\left[\left|\boldsymbol{h}_{\ell,\mathrm{k}}^* \boldsymbol{f}_k^{\mathrm{MF}}\right|^2\right] = N_a$.

Outline I

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

Downlink SQINR

Theorem

The output SQINR of the k-th uplink user is given by

$$\overline{\text{sqinr}}_k^{\text{MF}} = \frac{\alpha_d^2 \frac{G_k P_k}{N_a} \left| \mathbb{E}\left[\boldsymbol{h}_k^* \boldsymbol{f}_k^{\text{MF}} \right] \right|^2}{\overline{\text{den}}_d^{\text{MF}}} \tag{8}$$

where $\overline{\text{den}}_d^{\text{MF}}$ *is given by (9).*

$$\overline{\text{den}}_d^{\text{MF}} = \alpha_d^2 \frac{G_k P_k}{N_a} var\left[\boldsymbol{h}_k^* \boldsymbol{f}_k^{\text{MF}} \right] + \alpha_d^2 \sum_{k \neq k} \frac{G_k P_k}{N_a} \mathbb{E}\left[\left| \boldsymbol{h}_k^* \boldsymbol{f}_k^{\text{MF}} \right|^2 \right] + \sum_{k \neq k} T_{k,k} P_k^u \mathbb{E}\left[\left| \boldsymbol{g}_{k,k} \right|^2 \right]$$
$$+ \alpha_d^2 \sum_{\ell \neq 0} \sum_{k=0}^{K_\ell^d - 1} \frac{G_{\ell,k} P_{\ell,k}}{N_a} \mathbb{E}\left[\left| \boldsymbol{h}_{\ell,k}^* \boldsymbol{f}_{\ell,k}^{\text{MF}} \right|^2 \right] + \sum_{\ell \neq 0} \sum_{k=0}^{K_\ell^u - 1} T_{(\ell,k),k} P_{\ell,k}^u \mathbb{E}\left[\left| \boldsymbol{g}_{(\ell,k),k} \right|^2 \right]$$
$$+ \sum_{\ell} \frac{G_{\ell,k} P_{\ell,k}}{N_a} \mathbb{E}\left[\left| \boldsymbol{h}_{\ell,k}^* \boldsymbol{q}_\ell \right|^2 \right] + \sigma^2 \tag{9}$$

Outline I

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

Special Cases

Proposition

Considering a single-cell multiuser system (without any inter-cell interference) with perfect CSI, Corollary (in reverse link section) entails the results for downlink users in[a]*.*

[a] Dai, Liu, Wang, Zhao, Cheng, and Wang 2019.

Proposition

For channel hardening without full-duplexing (hence no co-channel interference between users) and with full-resolution ADC/DACs, we retrieve the results derived for downlink users in multicell massive MIMO systems 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.

Outline I

- Introduction
- Network Model
  - Description
  - Topology
  - Architecture
  - Model
- Reverse Link Analysis
  - Signal Model
  - Uplink SQINR
  - Special Cases
- Forward Link Analysis
  - Signal Model
  - Downlink SQINR
  - Special Cases

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

Effects of Data Converters Resolution

Lemma

For a fixed power budget, fixed number of transmit antennas and full-resolution ($b \to \infty$, $\alpha_u = \alpha_d = 1$), the spectral efficiencies for reverse and forward links converge to

$$\frac{\bar{\mathcal{I}}_k^u}{B} \to \log\left(1 + \frac{G_k P_k N_{\mathsf{a}}}{\sum_\ell \sum_k G_{\ell,k} P_{\ell,k} + P_{\mathsf{SI}} \mu_{\mathsf{SI}}^2 K^d N_{\mathsf{a}} + \sigma^2}\right) \quad (10)$$

$$\frac{\bar{\mathcal{I}}_k^d}{B} \to \log\left(1 + \frac{G_k P_k}{\sum_\ell \sum_k G_{\ell,k} P_{\ell,k} + \sum_\ell \sum_k T_{(\ell,k),k} P_{\ell,k}^u \sigma_{\mathsf{iui}}^2 + \sigma^2}\right) \quad (11)$$

- With fixed number of antennas, the spectral efficiency is constant.
- Through increasing ADC/DAC resolution to enhance the performance, the spectral efficiency is limited

Outline I

- Introduction
- Network Model
  - Description
  - Topology
  - Architecture
  - Model
- Reverse Link Analysis
  - Signal Model
  - Uplink SQINR
  - Special Cases
- Forward Link Analysis
  - Signal Model
  - Downlink SQINR
  - Special Cases

Outline II

Effects of Transmit Power

Lemma

For a fixed number of antennas, fixed b and when $P_{\mathsf{SI}} = P^d = P^u \to \infty$, the spectral efficiency converges to

$$\frac{\bar{\mathcal{I}}_k^u}{B} \to \log\left(1 + \frac{\alpha_u G_k N_{\mathsf{a}}}{\sum_\ell \sum_k G_{\ell,k} + (1-\alpha_u) G_k + \alpha_d N_{\mathsf{a}} \mu_{\mathsf{SI}}^2 \left[1 + \alpha_u \alpha_d (K^d - 1)\right]}\right) \quad (12)$$

$$\frac{\bar{\mathcal{I}}_k^d}{B} \to \log\left(1 + \frac{\alpha_d^2 G_k}{\alpha_d^2 \sum_\ell \sum_k G_{\ell,k} + \sum_\ell \sum_k T_{(\ell,k),k} \sigma_{\mathsf{iui}}^2 + \alpha_d (1-\alpha_d) \sum_\ell G_{\ell,k} (K_\ell^d + 1)}\right) \quad (13)$$

- The spectral efficiency depends on the number of antennas and quantization bits.
- Uplink and downlink spectral efficiencies are saturated by a ceiling caused by SI, IUI powers and quantization error, respectively.

Outline I

- Introduction
- Network Model
  - Description
  - Topology
  - Architecture
  - Model
- Reverse Link Analysis
  - Signal Model
  - Uplink SQINR
  - Special Cases
- Forward Link Analysis
  - Signal Model
  - Downlink SQINR
  - Special Cases

Outline II

- Asymptotic Analysis and Power Scaling Laws
  - Effects of Data Converters Resolution
  - Effects of Transmit Power
  - Power Scaling Laws
- System Performances
  - Performance Measures
  - Numerical Results
- Conclusion

Power Scaling Laws

Lemma

If the transmit powers of the BS and each user is scaled with the number of antennas N_a i.e., $P = \frac{E}{N_a}$ where E is fixed, as $N_a \to \infty$, the spectral efficiency converges to

$$\frac{\bar{\mathcal{I}}_k^u}{B} \to \log\left(1 + \frac{\alpha_u G_k E_k}{\alpha_d \mu_{\mathsf{SI}}^2 E_{\mathsf{SI}}\left[1 + \alpha_u \alpha_d (K^d - 1)\right] + \sigma^2}\right) \tag{14}$$

$$\frac{\bar{\mathcal{I}}_k^d}{B} \to \log\left(1 + \frac{\alpha_d^2 G_k E_k}{\sigma^2}\right) \tag{15}$$

- More antennas can eliminate intra-cell and inter-cell interference for uplink scenario.
- More antennas can eliminate the inter-user interference caused by full-duplexing for downlink scenario.
- The number of quantization bits determines the approximate uplink and downlink spectral efficiencies when the number of the antennas at a FD BS, N_a, goes to infinity.

Outline I

Outline II

Performance Measures

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

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

- Once a transmission strategy is specified, the corresponding cumulative distribution function (CDF) or outage probability for rate R (bit/s/Hz) is then

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

Outline I

- Introduction
- Network Model
  - Description
  - Topology
  - Architecture
  - Model
- Reverse Link Analysis
  - Signal Model
  - Uplink SQINR
  - Special Cases
- Forward Link Analysis
  - Signal Model
  - Downlink SQINR
  - Special Cases

Outline II

Numerical Results

Table 2: System Parameters.

Parameter	Value
Bandwidth	20 MHz
Pathloss Exponent (η)	3.5
Shadowing (σ_{dB})	5 dB
Downlink Transmit Power	40 W
Uplink Transmit Power	250 mW
SI Power (P_{SI})	40 W
SI Channel Power (μ_{SI})	10 dB
Thermal Noise Spectral Density	-174 dBm/Hz
Number of Antennas (N_{a})	100
Uplink/Downlink Users per Cell (K_ℓ)	10
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

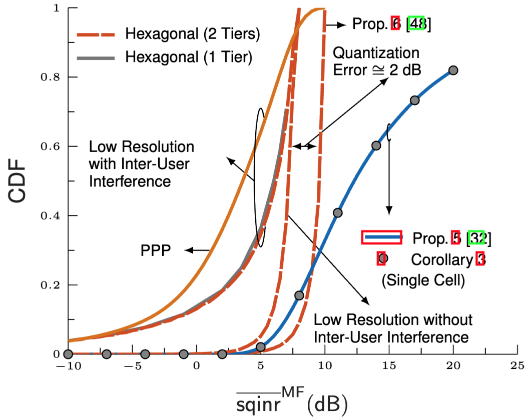


Figure 3: Forward link results: Effects of full-duplexing, quantization error, and network cell shapes on outage probability (CDF) with $\alpha_u = \alpha_d = 0.6$.

Spectral Efficiency

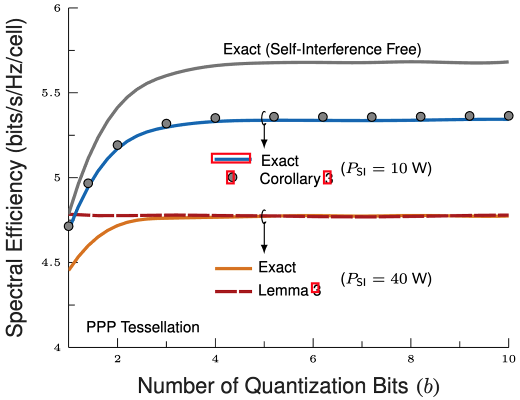


Figure 4: Reverse link spectral efficiency vs. number of quantization bits and SI power.

Spectral Efficiency

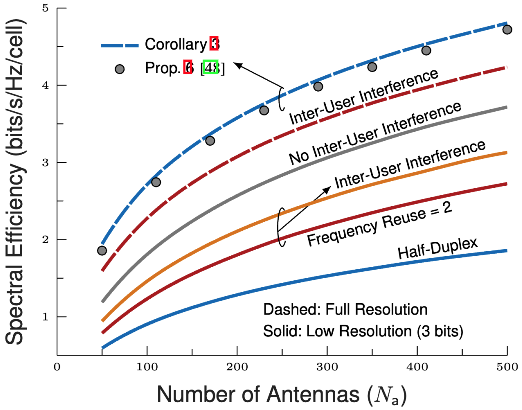


Figure 5: Forward link results: Effects of the number of antennas, duplexing modes, ADC/DAC resolution and frequency reuse factor on spectral efficiency with $\alpha_u = \alpha_d = 0.5$. Solid and dashed lines stand for low and full resolution ADC/DACs, respectively.

Conclusion

- Considered full-duplex multiantenna basestations
  - All-digital beamformers
  - Low-resolution data converters
  - Arranged on hexagonal lattice and PPP tessellation
- Developed a unified framework for reverse and forward links
  - Derived outage probability and spectral efficiency based on received signal, interference, quantization error, and thermal noise
  - Derived special cases
  - Carried out asymptotic analysis and power scaling laws
- Designed digital beamformers
  - Used degrees of freedom due to massive number of antennas
  - Compensated quantization error and interference
- Full duplex system outperforms half-duplex mode in 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