Energy efficiency of massive MIMO infrastructure

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Plan

(1-bit) downlink precoded massive MIMO

Multi-user massive MIMO [Marzetta2010]

aims to handle x00 of antenna at the BS with x0 single-antenna users

- benefit from huge increase in spatial diversity using mmWaves
- requires very low power consumption at each BS antenna

A potential solution is:

1-bit downlink massive MIMO

1-bit DAC means transmitted BPSK on both I and Q phases: $x = \pm 1 \pm j$

- low SNR loss at low to moderate SNR (operating point for mmWave massive MIMO) [Nossek2006]
- energy efficient PA (no power back-off), no gain control $\rightarrow$ simple RF

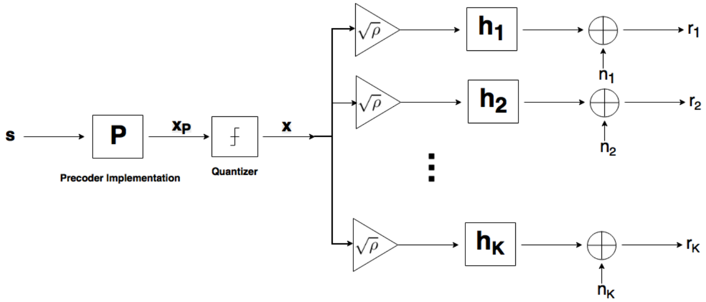
Question: what is the energy efficiency?

(1-bit) downlink precoded massive MIMO

- M-antenna BS transmits $\sqrt{\rho}\mathbf{x}$ to K single-antenna users, no power control,

  in order to send the QPSK symbol s_k to user $k \in [1, K]$
- user k receives: $r_k = \mathbf{h}_k \mathbf{x} + n_k$

  we denote $\mathbf{r} = [r_1 \ \cdots \ r_K]^T$ and $\mathbf{H} = [\mathbf{h}_1^T \ldots \mathbf{h}_K^T]^T$ the $K \times M$ channel matrix



1-bit downlink precoded massive MIMO

Notation: index $_{ZF}$ denotes the non-quantized signals

No index denotes the 1-bit quantized

1-bit transmitted vector on I and Q phases

M-antenna BS transmits:

$$\mathbf{x} = \mathcal{Q}(\mathbf{x}_{ZF}) = \mathcal{Q}(\mathbf{Gs}) = \text{sign}(\mathcal{R}(\mathbf{x}_{ZF})) + j\,\text{sign}(\mathcal{I}(\mathbf{x}_{ZF}))$$

where $\mathbf{x}_{ZF} = \mathbf{Gs}$ is the linearly precoded signal

with Zero-Forcing (ZF) precoding $\mathbf{G} = \mathbf{H}^H(\mathbf{HH}^H)^{-1}$

We use ZF for simplicity; MRC, MMSE and other non-linear precoders [SwindlehurstICASSP2018], [FijalkowAsilomar2017] are possible

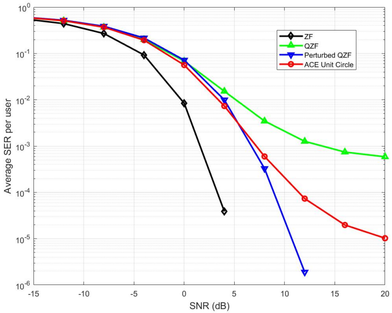
K single-antenna users directly decode received data (QPSK):

Decision at user k, $\hat{s}_k = \mathcal{Q}(r_k)$ is 1-bit ADC $\Rightarrow$

$$\hat{\mathbf{s}} = [\hat{s}_1, ..., \hat{s}_K]^T = \mathcal{Q}(\mathbf{r}) = \mathcal{Q}(\sqrt{\rho}\mathbf{Hx} + \mathbf{n})$$

(1-bit) downlink precoded massive MIMO

BER performance versus SNR:
$M = 128$-antenna, $K = 16$ single-antenna users, no power control



- 1-bit ZF
- non-linear 1-bit precoding: ACE [Asilomar'2017], vector-perturb. [Icassp'2018]
- ZF

Gap vanishes with $\gamma = M/K \approx 10$

Plan

Energy-Efficiency (EE)

$$\text{EE} = \frac{\text{Bit rate [bit/s]}}{\text{Energy consumption [Joule/s]}}$$

Bit rate of 1-bit DL massive MIMO

$$r_B = B \sum_{k=1}^{K} \log_2 \left(1 + \mathrm{SQINR}_k\right)$$

For M and $K \to \infty$, finite $\gamma = \frac{M}{K} > 1$ and full row-rank matrix with **H** i.i.d components of variance σ^2 (equal path loss), [SaxenaTSP2017][a] shows, using random matrix theory tools that:

- multi-users interference vanishes
- all SQINR_k become equal, so:

$$r_B \approx BK \log_2 \left(1 + \frac{\frac{2(\gamma-1)^2}{\gamma\pi}}{\left(1-\frac{2}{\pi}\right)\left(1-\frac{1}{\gamma}\right)+\frac{\sigma_n^2}{2\rho\sigma^2}} \right) := B\frac{M}{\gamma} r(\gamma)$$

[a] AK Saxena, I Fijalkow, AL Swindlehurst, "Analysis of One-Bit Quantized Precoding for the Multiuser Massive MIMO Downlink", IEEE Tr on Signal Processing, 2017

Energy consumption model

Energy consumption $= P_{TX}$ (BS power amplifiers) $+ P_{CP}$ (BS + UE circuits)

In many studies, $P_{CP} \approx P_{FIX}$ infrastructure (cooling), load independent.

However, when M and $K \to \infty \Rightarrow$ more elaborate model for circuit power consumption is needed [BjornsonTWC2015].

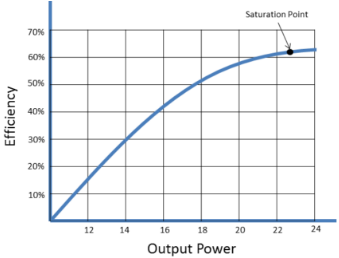
EE of 1-bit DL massive MIMO

Energy consumption of M power amplifiers

$$P_{TX} = \frac{BE[\|\mathbf{x}\|^2]}{\eta} = \frac{2MB\rho}{\eta}$$

η is the power amplifier efficiency, can be up to 0.6 for constant envelope (QPSK) signals [Gautier2014]

Power amplifier efficiency versus antenna transmitted power $2B\rho$:



EE of 1-bit DL massive MIMO

For the DL:

$$P_{CP} = P_{FIX} + P_{TC} + P_{C/D} + P_{BH} + P_{LP}$$

- RF: scaling with M (DAC, mixers, filters) or K (LNA, mixer, filter) : $P_{TC} = MP_{BS} + \gamma MP_{UE} + P_{SYN}$
- channel encoding and decoding: scales with rate $P_{C/D} = r_B(P_{COD} + P_{DEC}) \approx B\frac{M}{\gamma}r(\gamma)(P_{COD} + P_{DEC})$ with P_{COD} and P_{DEC} in W/bit/s
- power backhaul: scales with rate $P_{BH} = r_B P_{BT} \approx B\frac{M}{\gamma}r(\gamma)P_{BT}$
- ZF precoding: $P_{LP} = B(\frac{K^3}{3L_{BS}} + 3\frac{MK^2+MK}{L_{BS}}) = \frac{BM^2}{L_{BS}}(\frac{M}{3\gamma^3} + \frac{3M}{\gamma^2} + \frac{3}{\gamma})$ using Cholesky decomposition, L_{BS} : nb arithmetic complex-valued operations per Joule (in [flops/W])

EE of 1-bit DL massive MIMO

EE expression for 1-bit DL massive MIMO

For M and $K \to \infty$, finite $\gamma = \frac{M}{K} > 1$ and known full row-rank matrix $\mathbf{H}$ with i.i.d components of variance σ^2

$$EE \approx \frac{M\frac{r(\gamma)}{\gamma}}{\frac{P_{FIX}+P_{SYN}+M(P_{BS}+\frac{P_{UE}}{\gamma})}{B} + \frac{2M\rho}{\eta} + M\frac{r(\gamma)(P_{COD}+P_{DEC}+P_{BT})}{\gamma} + \frac{M^2}{L_{BS}}(\frac{M}{3\gamma^3} + \frac{3M}{\gamma^2} + \frac{3}{\gamma})}$$

with $r(\gamma) = \log_2(1 + \frac{\frac{2(\gamma-1)^2}{\gamma\pi}}{(1-\frac{2}{\pi})(1-\frac{1}{\gamma})+\frac{\sigma_n^2}{2\rho\sigma^2}})$

Approximations:

- If we consider only the power amplifier consumption, $EE \approx \frac{\eta r(\gamma)}{2\rho\gamma}$ depends only on γ.
- For $M \to \infty$, finite γ $EE \approx \frac{L_{BS}\gamma^2 r(\gamma)}{3M^2}$, precoding computation is predominent

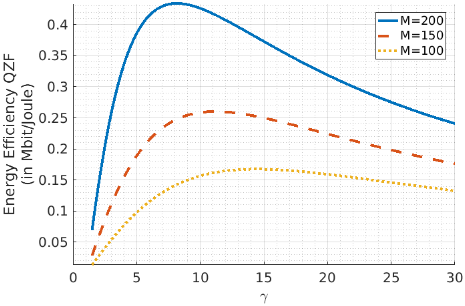
EE of 1-bit DL massive MIMO: simulation

B	20 MHz	ρ	1 W/MHz
P_{BO}	8.5dB	$\zeta = 1/\sigma^2$	1
P_{FIX}	18 W	$P_{COD} + P_{DEC}$	0.9 W/Gbit/s
P_{SYN}	2 W	P_{BT}	0.25 W/Gbit/s
P_{BS}	1 W	L_{BS}	12.8 Gflops/W
P_{UE}	0.1 W		
η	0.6		

Table : Simulation parameters from [BjornsonTWC2015]

EE of 1-bit DL massive MIMO: simulation

We display EE versus γ:



- EE depends not only on $\gamma \Rightarrow$ we can not limit the study to the power amplifier power consumption
- maximum EE decreasing with M
- optimal value of γ around 10, decreasing with M

Plan

EE_{ZF}

ZF precoder ⇒ no MUI, $\hat{\mathbf{s}} = \mathcal{Q}(\mathbf{s} + \mathbf{n})$

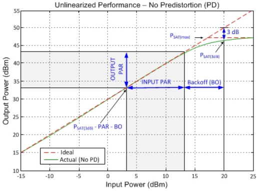
$$\text{EE}_{ZF} = \frac{\text{Bit rate}_{ZF}\ [\text{bit/s}]}{\text{Energy consumption}_{ZF}\ [\text{Joule/s}]} = \frac{B\frac{M}{\gamma}\log_2(1 + SNR)}{\text{Energy consumption}_{ZF}\ [\text{Joule/s}]}$$

Goal: we want to make a fair comparison between EE and EE_{ZF}

- equal average transmit power [SaxenaTSP2017] doesn't consider power amplifier saturation ⇒ non-equal average transmit power
- taking into account the signal dynamic range ⇒ power back-off
- change the number of antenna to compensate for rate loss ?

Power back-off

Transmitted signal $\mathbf{x}_{ZF}$ is not constant modulus, $\mathbf{x}_{ZF} = \mathbf{Gs}$



$\Rightarrow$ the high values of $\rho_{ZF}|x_{ZF,m}|^2$ will be saturated

Average transmitted power

$$E[\|\mathbf{x}_{ZF}\|^2] = \mathrm{trace}(E[\mathbf{x}_{ZF}^H \mathbf{x}_{ZF}]) = 2\rho_{ZF}\ \mathrm{trace}(E[(\mathbf{HH}^H)^{-1}])$$

For M and $K \to \infty$, finite $\gamma = \frac{M}{K} > 1$ and full row-rank matrix with $\mathbf{H}$ i.i.d components of variance σ^2 (equal path loss), [SaxenaTSP2017] shows $E[\|\mathbf{x}_{ZF}\|^2] \approx 2\rho_{ZF}\frac{1}{\sigma^2(\gamma-1)}$

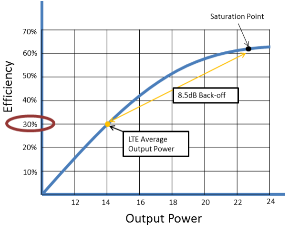
Power back-off P_{BO} to avoid signal saturation in power amplifier

$$P_{BO}\ \text{[in dB]} = 10\log\left(\frac{E[\|\mathbf{x}_{ZF}\|^2]}{E[\|\mathbf{x}\|^2]}\right) = 10\log(M\rho) - 10\log\left(\frac{\rho_{ZF}}{\sigma^2(\gamma-1)}\right)$$

Power back-off impact on efficiency

$P_{BO} \Rightarrow$ power amplifier efficiency reduces

Display of power amplifier efficiency
versus average power transmitted per antenna $\frac{E[\|\mathbf{x}_{ZF}\|^2]}{M}$



For LTE (OFDM precoding), $P_{BO} = 8.5\text{dB}$ $\Rightarrow$ efficiency is reduced to $\eta_{ZF} = 0.3$ $\Rightarrow$ we consider these values

EE of DL massive MIMO

Energy consumption of M power amplifiers

$$P_{TX,ZF} \approx \frac{2B\rho_{ZF}}{\eta_{ZF}} \frac{1}{\sigma^2(\gamma-1)}$$

We assume $P_{CP,ZF}$ is modeled as P_{CP} with respect to r_{ZF}, M and γ

EE expression of 1-bit DL massive MIMO

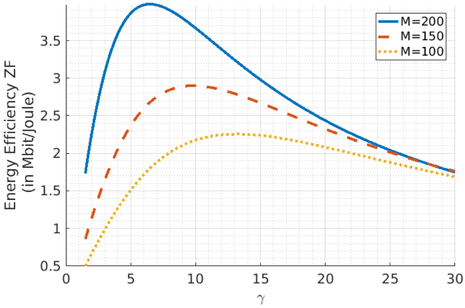
For M and $K \to \infty$, finite $\gamma = \frac{M}{K} > 1$ and known full row-rank matrix $\mathbf{H}$ with i.i.d components of variance σ^2,

$$EE_{ZF} \approx \frac{M\frac{r_{ZF}}{\gamma}}{\frac{P_{FIX}+P_{SYN}+M(P_{BS}+\frac{P_{UE}}{\gamma})}{B} + \frac{2\rho_{ZF}}{\eta_{ZF}}\frac{1}{\sigma^2(\gamma-1)} + M\frac{r_{ZF}(P_{COD}+P_{DEC}+P_{BT})}{\gamma} + \frac{M^2}{L_{BS}}(\frac{M}{3\gamma^3}+\frac{3M}{\gamma^2}+\frac{3}{\gamma})}$$

with $r_{ZF} = \log_2(1+\frac{2\rho_{ZF}}{\sigma_n^2})$

EE of DL massive MIMO: simulation

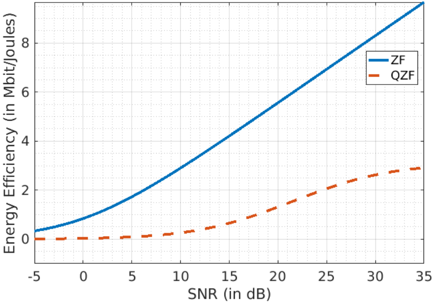
With the same simulation parameters, we display EE_{ZF} versus γ:



- EE_{ZF} has similar shape than EE, with larger values
- for large γ, EE_{ZF} depends on γ only $\Rightarrow$ power amplifier consumption is dominent

EE of DL massive MIMO: comparison

With the same simulation parameters, we display EE and EE_{ZF} versus SNR, for $M = 150$ and $\gamma = 10$:



- EE difference between 1-bit and ZF grows with SNR
- for low SNR, they are comparable
  $\Rightarrow$ should we increase M for the 1-bit scheme to compensate rate loss ?

Conclusion

A preliminary study of the energy efficiency for (1-bit) DL massive MIMO ZF precoding, [ISWCS'2019] we show:

- 1-bit EE has similar behavior than EE_{ZF}, but with smaller values
- γ is an important parameter and could be optimized
- M also matters (one can not restrict to the power amplifier)

A fair comparison is not easy $\Rightarrow$ future investigation:

- study PAPR to get a more relevant P_{BO} value
- ensure the SNR is in low to moderate values
- change M to ensure almost equal rates
- consider many 1-bit antenna and a few non-quantized antenna to equal rates

[ISWCS'2019] A. Marcastel, I. Fijalkow, L. Swindlehurst,

Energy efficient downlink massive MIMO: Is 1-bit quantization a solution ?, ISWCS, Oulu, Finland, August 2019.