Downlink Multicell Processing Employing QAM Quantization under a Constrained Backhaul

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Outline

- System Model
- Quantized QAM Design and Transmission
- Problem Optimization
- Numerical results
- Conclusions

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System Model (1/3)

- BSs coordination or multicell processing has been recognized as a promising solution to reduce inter-cell interference and improve spectral efficiency in cellular network
- BSs share both channel state information (CSI) and data for the MTs in all the cells and cooperate in the transmission by implementing a distributed multi antenna system
- Issue: the sharing of CSI and data among BSs requires an higher backhaul throughput, which is not provided by current cellular systems
  - We assume that for each MT the serving BS has a full knowledge of its related message, whereas the auxiliary BSs have only a partial knowledge

System Model (2/3)

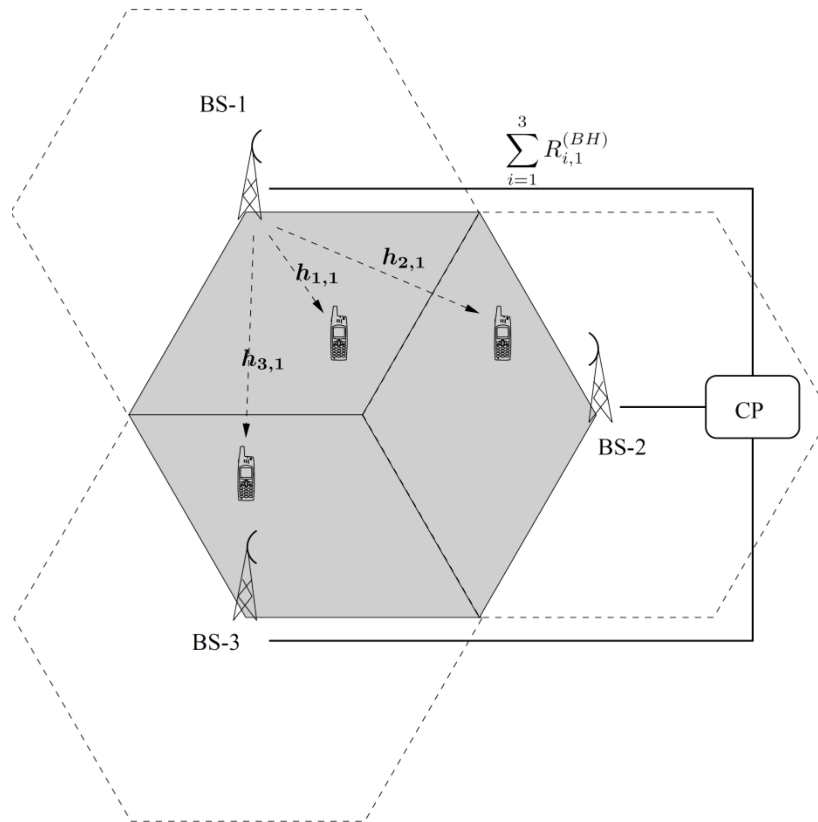
- *K* BSs with *N* antennas serving *K* single-antenna MTs
- Backhaul constraint for BS *j* is

$$\sum_{i=1}^{K} R_{i,j}^{(BH)} \leq \bar{R}^{(BH)} \quad (1)$$

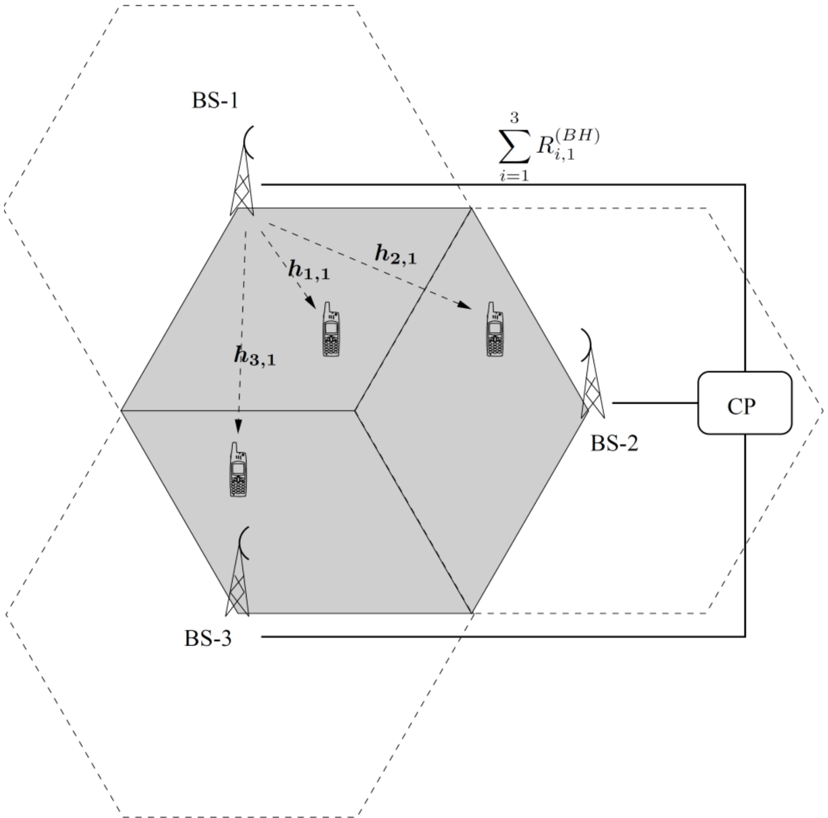
where $R_{i,j}^{(BH)}$ is the backhaul throughput used by the CP to transmit data message of MT *i* to BS *j*

- $\boldsymbol{h}_{i,k}$ is the *Nx1* channel between BS *k* and MT *i* and we define

$$\boldsymbol{h}_i = [\boldsymbol{h}_{i,1}^T, \boldsymbol{h}_{i,2}^T, \ldots, \boldsymbol{h}_{i,K}^T]^T$$



System Model (3/3)



- For each MT *i* all BSs cooperative transmit signal $d_i^{(q)}$ employing beamformer

$$\boldsymbol{v}_i = [\boldsymbol{v}_{i,1}^T, \boldsymbol{v}_{i,2}^T, \ldots \boldsymbol{v}_{i,K}^T]^T$$

  while the serving BS *i* transmits also signal $d_i^{(e)}$ employing beamformer $\boldsymbol{w}_i$

- Signal tx. by BS *j* and the power constraint on the same BS are

$$\boldsymbol{z}_j = \boldsymbol{w}_j d_j^{(e)} + \sum_{i=1}^{K} \boldsymbol{v}_{i,j} d_i^{(q)} \qquad \mathrm{E}\left[\left|d_j^{(e)}\right|^2\right] + \sum_{i=1}^{K} V_{i,j} \mathrm{E}\left[\left|d_i^{(q)}\right|^2\right] \leq \bar{P}_{MAX}$$

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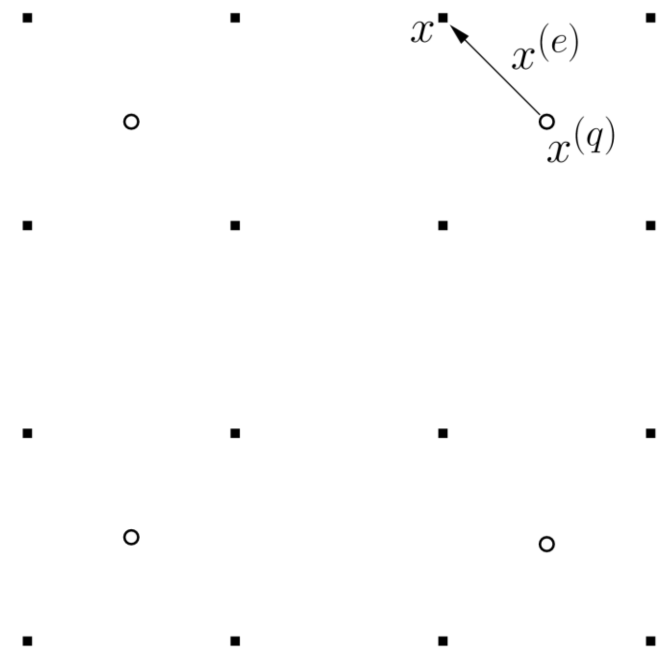
Quantized QAM Transmission

- Let x_i be the QAM symbol with zero mean and unitary power intended to MT i, $x_i^{(q)}$ its quantized version and $x_i^{(e)} = x_i - x_i^{(q)}$ the quantization error
- We assume transmitted signals are

$$d_i^{(q)} = \sqrt{P_i^{(q)}} x_i^{(q)} \,, \; d_i^{(e)} = \sqrt{P_i^{(e)}} x_i^{(e)}$$

- To guarantee the reconstruction of the full QAM at the MT i we impose

$$\boldsymbol{h}_{i,i}^T \boldsymbol{w}_i \sqrt{P_i^{(e)}} = \boldsymbol{h}_i^T \boldsymbol{v}_i \sqrt{P_i^{(q)}}$$



Quantized QAM Design

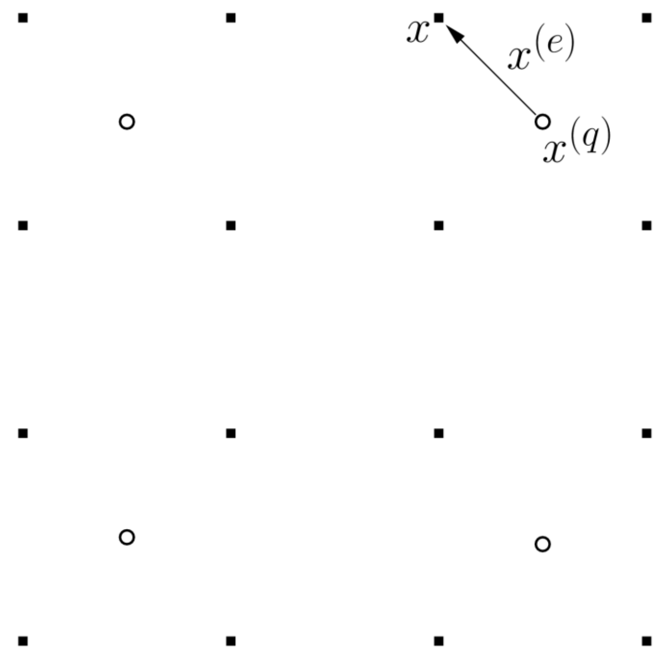
- Let 2^{b_i} and $2^{b_i^{(q)}}$ be the sizes of full and quantized constellations where $b_i^{(q)} \in \{0,1,\ldots,b_i\}$
- By imposing

$$\mathrm{E}\left[x_i^{(e)}\right] = 0$$

$$\mathrm{E}\left[x_i^{(q)*} x_i^{(e)}\right] = 0$$

we can write

$$\gamma_i = \mathrm{E}\left[\left|x_i^{(e)}\right|^2\right] = \frac{2^{b_i - b_i^{(q)}} - 1}{2^{b_i} - 1}$$



Spectral Efficiency on the Air

- Let

$$G_i^{(e)} = \left|\boldsymbol{h}_{i,i}^T \boldsymbol{w}_i\right|^2 \qquad G_{i,j}^{(I_e)} = \left|\boldsymbol{h}_{i,j}^T \boldsymbol{w}_j\right|^2$$

$$G_i^{(q)} = \left|\boldsymbol{h}_i^T \boldsymbol{v}_i\right|^2 \qquad G_{i,j}^{(I_q)} = \left|\boldsymbol{h}_i^T \boldsymbol{v}_j\right|^2$$

- The SINR at MT *i* can be written as

$$\mathrm{SINR}_i = \frac{G_i^{(q)} P_i^{(q)}}{\sigma_n^2 + \sum_{j=1, j\neq i}^{K} \left[G_{i,j}^{(I_e)} \frac{G_j^{(q)}}{G_j^{(e)}} \gamma_j + G_{i,j}^{(I_q)} (1-\gamma_j) \right] P_j^{(q)}}$$

- We approximate the spectral efficiency on air for MT *i* as

$$R_i = \min\left\{ \log_2\left(1 + \frac{\mathrm{SINR}_i}{\Gamma_{\mathrm{GAP}}}\right), b_i \right\}$$

Backhaul Throughput

- The exact value of $R_{i,j}^{(BH)}$ could be obtained by implementing entropy coding on the sequence of bits after quantization (very high complexity)
- Let $r_i^{(q)} = b_i^{(q)}/b_i$, we assume

$$R_{i,j}^{(BH)} \simeq \begin{cases} R_i, & j = i\,, \\ \min\left\{R_i,\, r_i^{(q)}\ b_i\right\}, & j \neq i\,. \end{cases}$$

- The serving BS *i* receives all data bits, whereas for each auxiliary BS *j*≠*i* the CP makes the better choice between transmitting at full spectral efficiency R_i or performing channel coding and then transmitting only the sequence of bits representing the quantized QAM symbols

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Optimal Power Allocation

- By imposing the reconstruction of the full QAM symbol at the MTs, the power constraint at BS *j* becomes

$$\gamma_j \frac{G_j^{(q)}}{G_j^{(e)}} P_j^{(q)} + \sum_{i=1}^{K} V_{i,j}(1-\gamma_i) P_i^{(q)} \leq \bar{P}_{MAX} \qquad (2)$$

- The problem of maximizing the network spectral efficiency can be expressed as

$$R^{(DATA)} = \max_{\{b_i, r_i^{(q)}, P_i^{(q)} \geq 0\}} \sum_{i=1}^{K} R_i$$

s.t. (1) and (2)

Equal Power Allocation (1/2)

- As the network spectral efficiency is a non-convex function w.r.t. $P_i^{(q)}$, we focus on the case that the total power allocated by the BSs to each MT is the same by imposing

$$P_i^{(q)}\left[\gamma_i \frac{G_i^{(q)}}{G_i^{(e)}} + (1-\gamma_i)\right] = \bar{P}$$

- The K power constraints in (2) become now a simple upper bound on the variable $\bar{P}$

$$\bar{P} \leq \frac{\bar{P}_{MAX}}{\max_{j=1,2,\ldots,K}\left\{\frac{\gamma_j G_j^{(q)}}{\gamma_j G_j^{(q)} + (1-\gamma_j)\,G_j^{(e)}} + \sum_{i=1}^{K} \frac{V_{i,j}(1-\gamma_i)G_i^{(e)}}{\gamma_j G_j^{(q)} + (1-\gamma_j)\,G_j^{(e)}}\right\}} \qquad (3)$$

Equal Power Allocation (2/2)

- Assuming equal power allocation among the MTs, the optimization problem can be written as

$$R^{(DATA)} = \max_{\left\{b_i, r_i^{(q)}, \bar{P}\right\}} \sum_{i=1}^{K} R_i$$

  s.t. (1) and (3)

- Now the objective function and the left-hand side of backhaul constraints are monotonically nondecreasing functions in the variable $\bar{P}$
- The optimization problem can be solved with an exhaustive search among the quantization parameters $\left\{b_i, r_i^{(q)}\right\}$ and, for each set, with a dichotomic search in the variable $\bar{P}$

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Simulation Setup (1/2)

- We consider *K = 3* BSs each equipped with *N = 1* antenna
- Channel model includes a path-loss coefficient of 3.5, shadowing with standard deviation of 8.9 dB and i.i.d. Rayleigh fading
- $\bar{P}_{MAX}$ = 40 dBm and σ_n^2 = -108 dBm
- $b_i \in \{2, 4, 6\}$ and $\Gamma_{\text{GAP}} = 1$
- Beamformers $\boldsymbol{v}_i$ are designed using a ZF criterion, whereas beamformers $\boldsymbol{w}_i$ only compensate channel phases

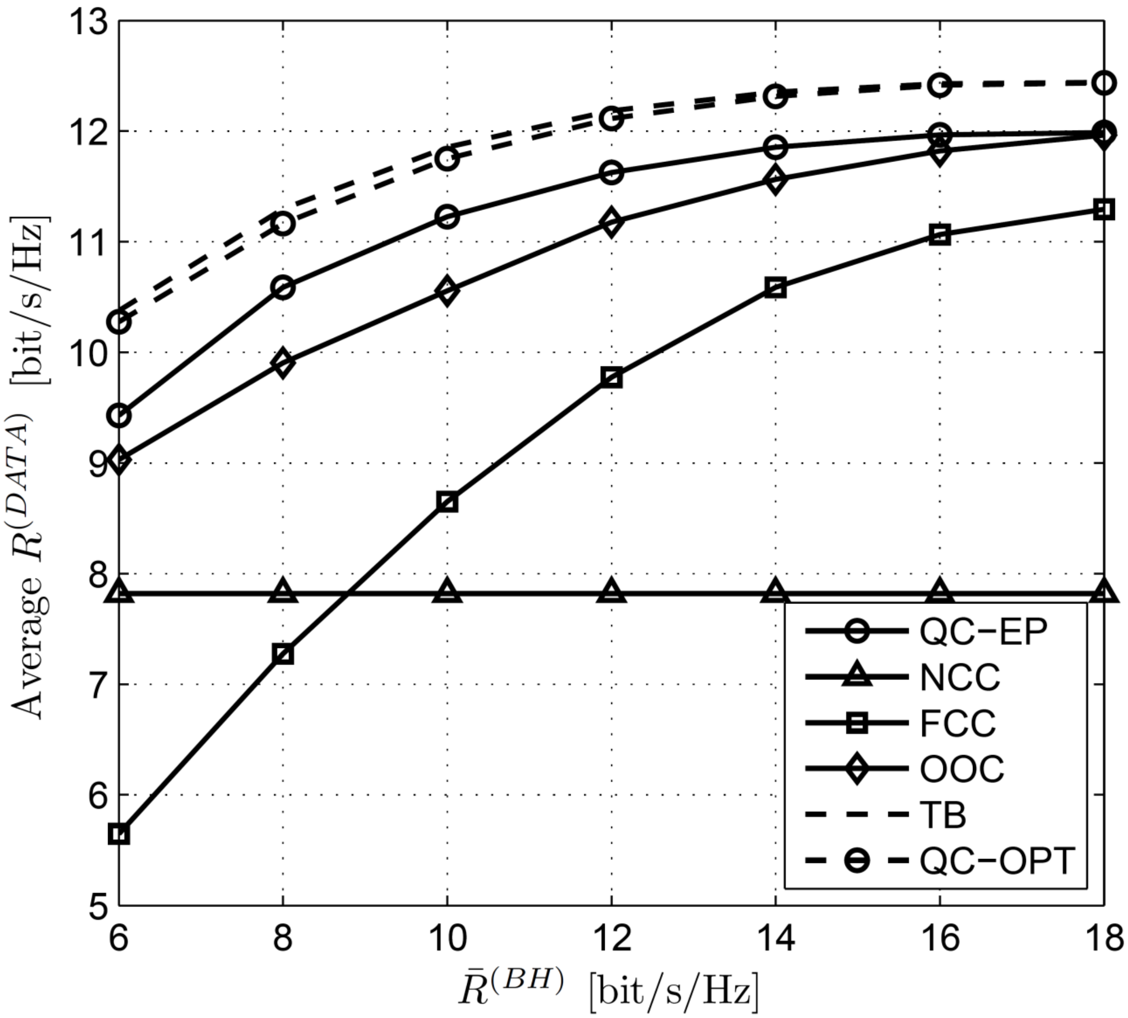
Simulation Setup (2/2)

- The proposed solution (QC-EP) is compared in terms of network spectral efficiency $R^{(DATA)}$ and backhaul throughput for a single BS $R^{(BH)}$ against
  - FCC: all BSs share data of MTs (i.e. $r_i^{(q)} = 1$, for all i)
  - NCC: no cooperation among BSs is allowed (i.e. $r_i^{(q)} = 0$, for all i)
  - OOC: cooperation without quantization allowed (i.e. $r_i^{(q)} \in \{0,1\}$, for all i)
- FCC, NCC and OOC are evaluated assuming eq. pow. all.
- As upper bound we consider (QC-OPT) and a theoretical bound (TB) obtained by applying Slepian-Wolf encoding

TB Obtained with Slepian-Wolf Encoding

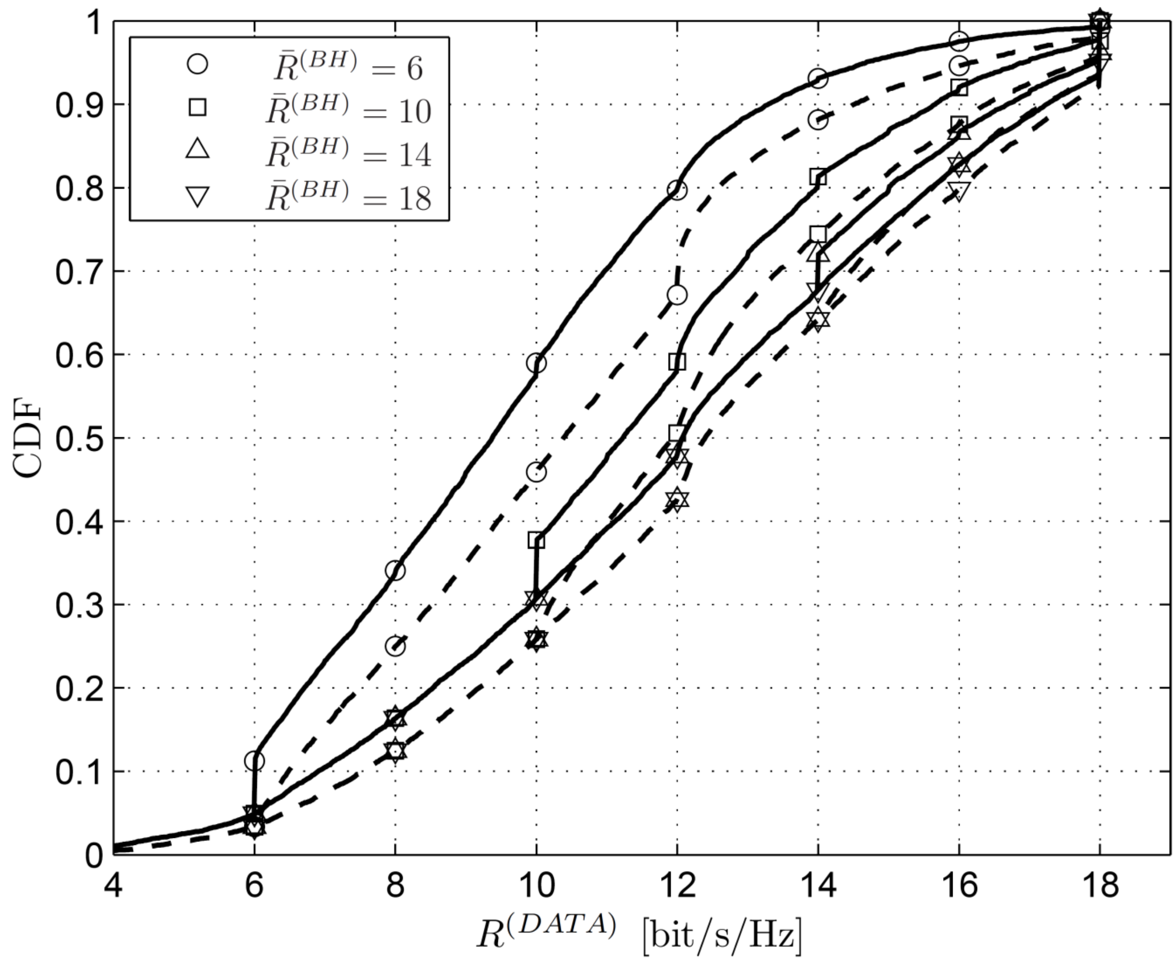
- Under the assumption that each MT *i* treats the other MTs' signal as interference, the system between each MT and the BSs can be modeled as a MAC with correlated sources
- BSs jointly transmit a common message using $\boldsymbol{v}_i$
- Serving BS transmits a private message using $\boldsymbol{w}_i$
- Each MT employs successive interference cancellation (SIC) to decode both messages

Average $R^{(DATA)}$

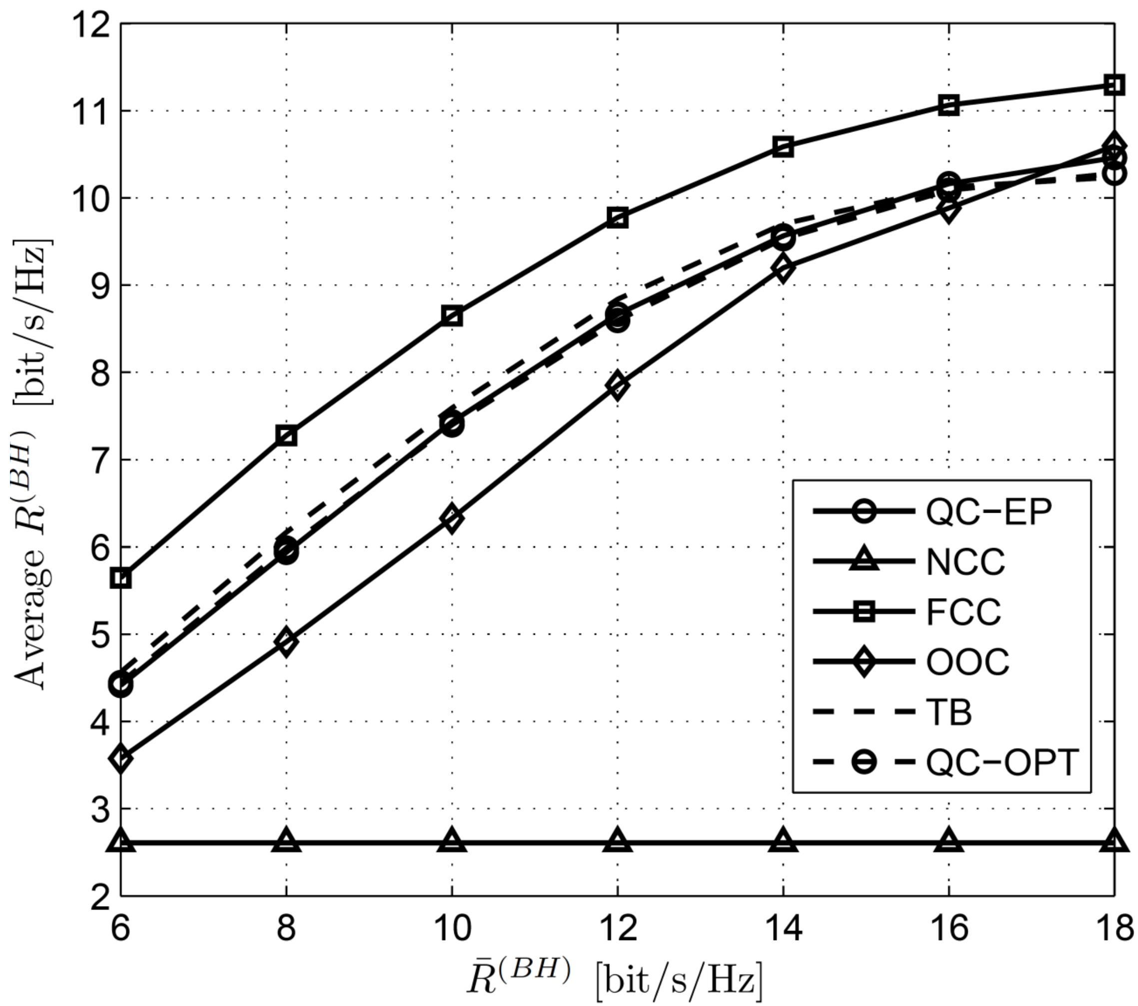


CDF of $R^{(DATA)}$

- QC-EP: continuos lines
- TB: dashed lines



Average $R^{(BH)}$



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- QC-EP outperform all the other schemes in which the sharing of partial information is not allowed
- QC-EP performs close to QC-OPT and TB with a significant reduction of design and implementation complexity
  - It does not require SIC at the MTs

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Thank you for your attention

Questions?