Energy-Efficient Techniques for 5G Cellular and IoT Networks

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Outline

- Introduction
- Energy consumption in modern wireless networks
- Energy-efficient channel estimation
- Energy-efficient interference mitigation
  - Iterative detection and decoding for the uplink
  - Precoding for the downlink
- Ongoing and future work
- Conclusions

Introduction (1/2)

- 5G key requirements:
  - High data rates and spectral efficiency.
  - Reliable links.
  - Low cost and low energy consumption.
  - Support to cellular, IoT and other use cases such as machine-type communications.

- 5G technologies:
  - Large-scale multiple-antenna systems.
  - Cloud-radio access networks (CRANs).
  - Distributed antenna systems, small cells and cell-free concepts.

Introduction (2/2)

Key problems:

- Energy consumption grows with the number of antenna elements at the access points and the user terminals.
- Energy consumption is also governed by the number of bits employed at analog-to-digital converters (ADCs) and digital-to-analog converters (DACs).
- Most systems to date employ ADCs and DACs with a large number of bits, i.e., greater than 8 bits.

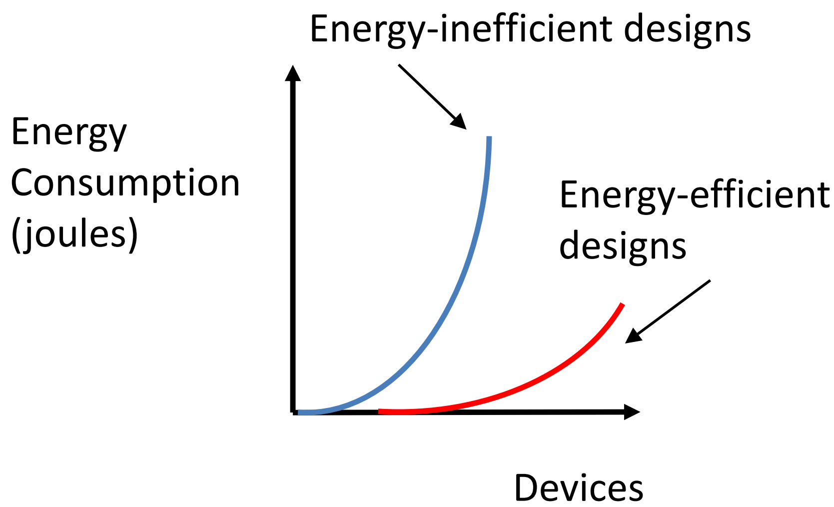
Our contributions:

- We present a framework for energy-efficient design of several tasks in 5G cellular and IoT networks using coarsely quantized signals (1-3 bits) based on signal processing.
- We develop several energy-efficient design approaches that employ compensation techniques for recovering losses resulting from the low resolution signals.
- The proposed approaches can be used for designing several functions in 5G networks and can approach optimal performance.

Energy consumption (1/2)

- Energy consumption depends on several aspects of hardware, system architecture and tasks performed by devices such as:
  - Signal processing
  - Coding
  - RF chain and circuits
  - Network architecture

- Other sources of energy consumption:
  - Number of cells and access points
  - Protocols and signalling



Energy consumption (2/2)

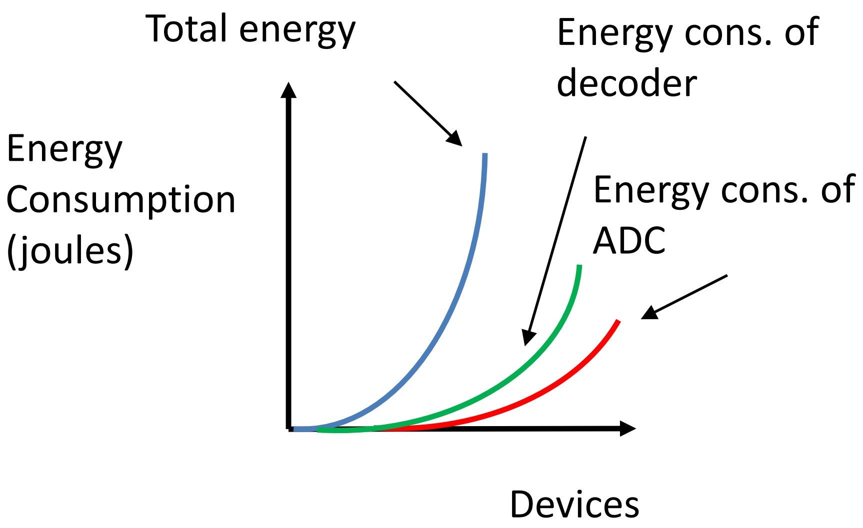
- Mathematical details (uplink perspective):

$$E_{total} = E_{PA} + E_{ADC} + E_{LNA} + E_{DEC},$$

- The decoding task is responsible for most of the energy consumption.

- ADCs and DACs are also two major sources of energy consumption, which scales with the number of bits used to represent samples

- Network architecture and location of antenna also play a key role due to the propagation aspects.



A. Mezghani and J. A. Nossek, "Power efficiency in communication systems from a circuit perspective," *2011 IEEE International Symposium of Circuits and Systems (ISCAS)*, Rio de Janeiro, 2011, pp. 1896-1899.

S. Cui, A. J. Goldsmith and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," in IEEE Journal on Selected Areas in Communications, vol. 22, no. 6, pp. 1089-1098, Aug. 2004.

Uplink system model and main tasks (1/2)

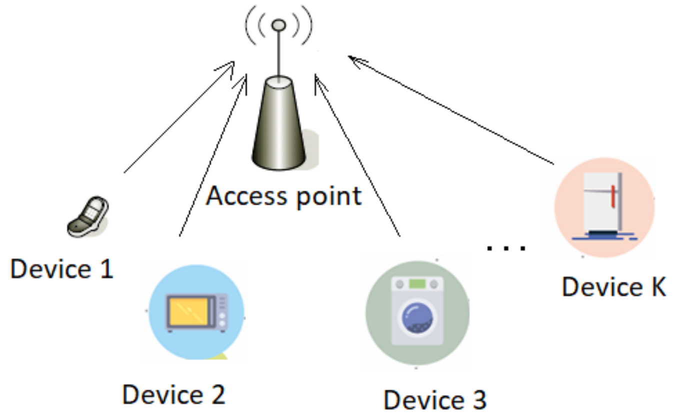
- We consider an uplink model of a network with K devices in a cell that are served by an access point:

$$\boldsymbol{r} = \sum_{k=1}^{K} \boldsymbol{H}_k \boldsymbol{s}_k + \boldsymbol{n}$$

- The network architecture could be structured as
  - Cellular network
  - Cell-free network with distributed antennas

- ADCs, decoding, AGCs and RF chain are key for energy consumption

- Key tasks of devices and access points:
  - Channel estimation
  - Interference mitigation using iterative detection and decoding



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Downlink system model and main tasks (2/2)

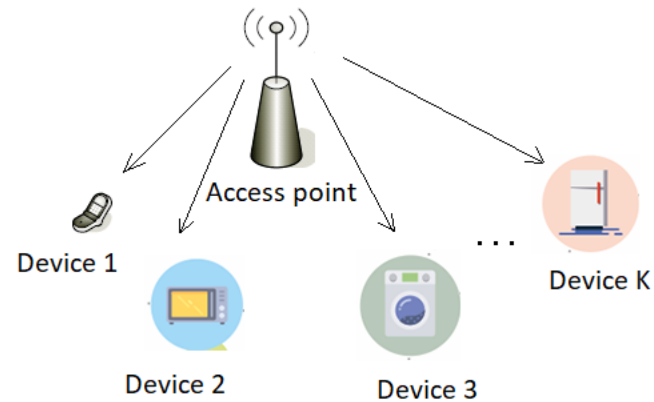
- We also consider a downlink model of a network with K devices in a cell that are served by an access point:

$$\boldsymbol{r} = \sum_{k=1}^{K} \boldsymbol{H}_k \boldsymbol{P}_k \boldsymbol{s}_k + \boldsymbol{n}$$

- The network architecture can be structured as
  - Cellular network
  - Cell-free network with distributed antennas

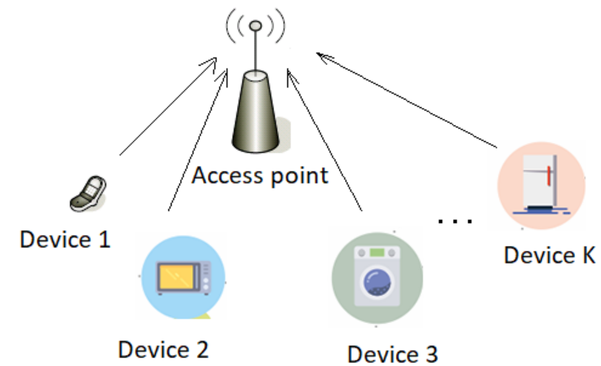
- DACs, decoding and RF chain are key for energy consumption

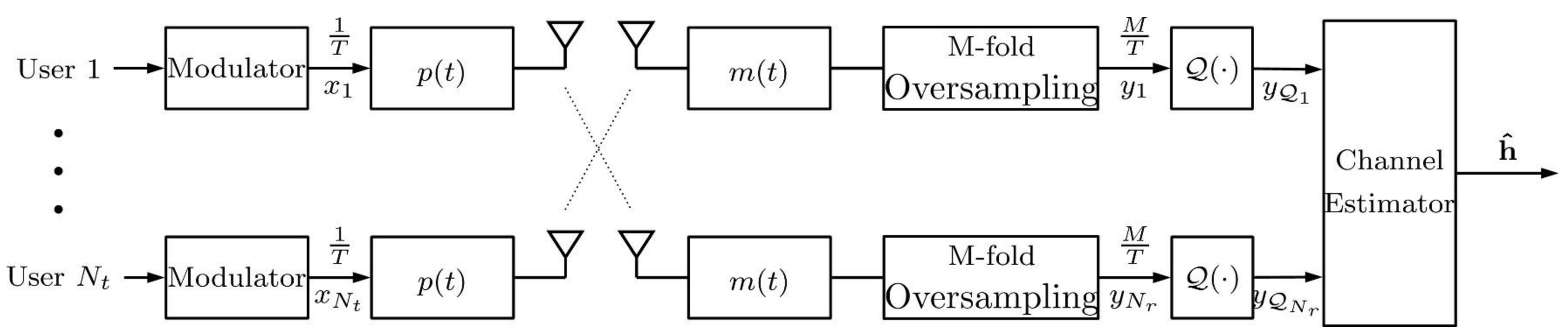
- Key tasks of devices and access points:
  - Interference mitigation using precoding
  - Power allocation and scheduling



Energy-efficient channel estimation (1/3)

- Channel estimation is a key task in IoT and cellular 5G networks
- An energy-efficient channel estimation approach employs coarse quantization (1-3 bits to represent each sample)
- Compensation techniques include:
  - Compensation of the estimator,
  - Low-resolution-aware (LRA) design of filters
  - Oversampling





Energy-efficient channel estimation (2/3)

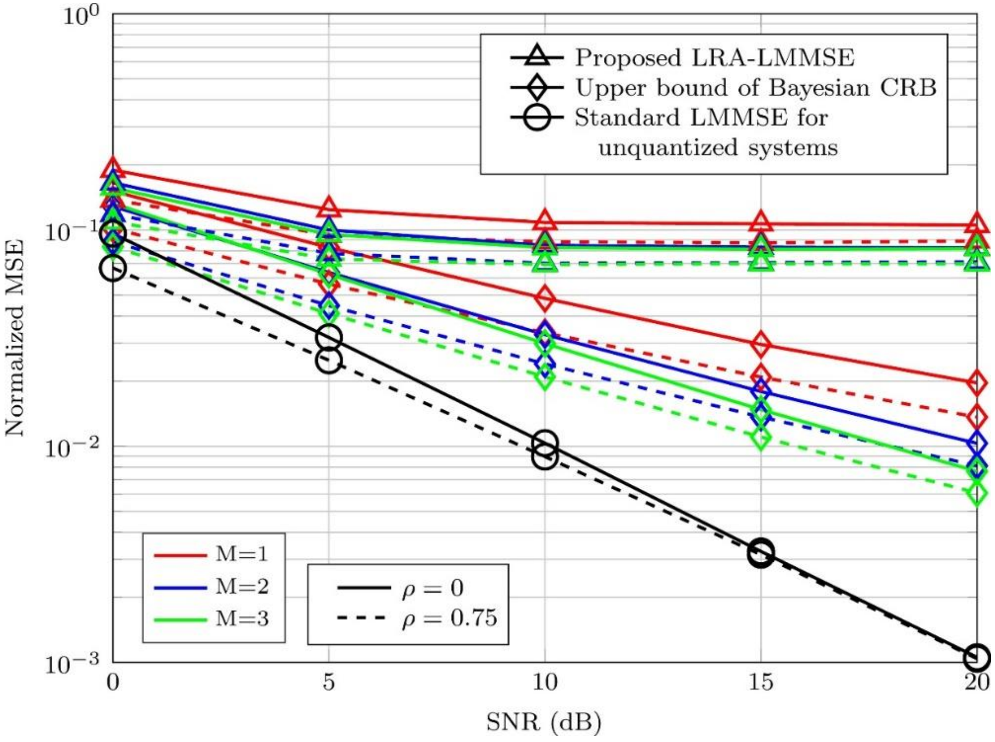
- We consider a multiuser system with N_t = 1 transmit antennas, K =6 users, N_r= 16 receive antennas and 40 pilots.

- The model is given by

$$\boldsymbol{r} = \sum_{k=1}^{K} \boldsymbol{H}_k \boldsymbol{s}_k + \boldsymbol{n}$$

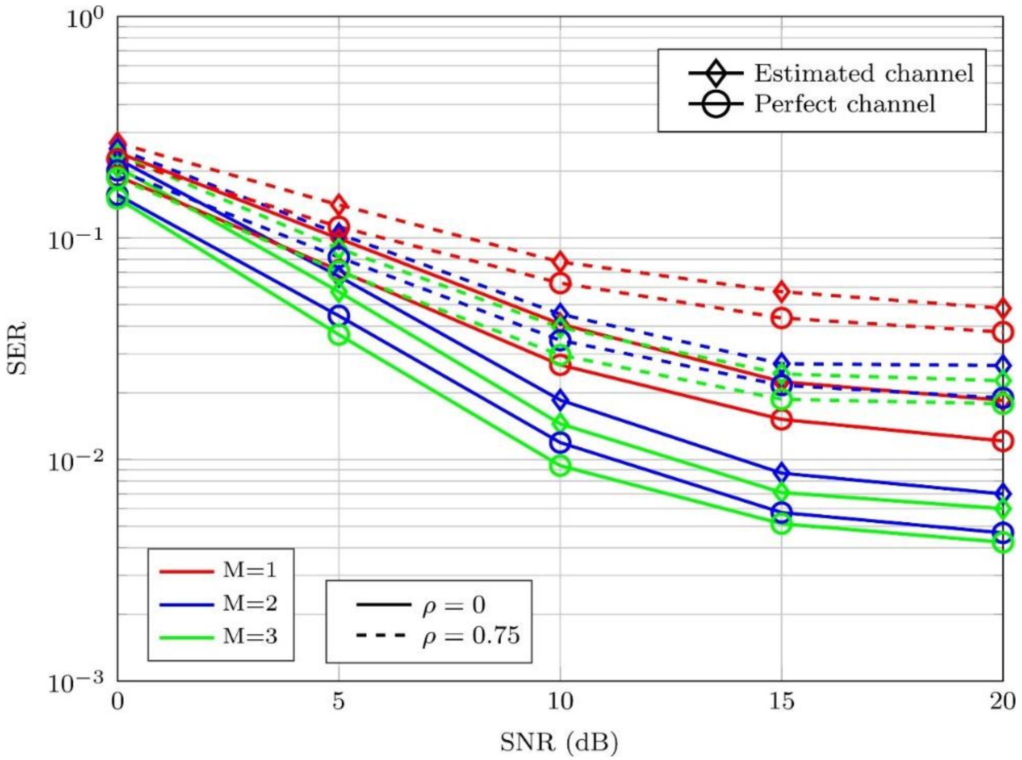
- Problem: to estimate $\boldsymbol{H}_k$

- Oversampling-based channel estimator can significantly improve the performance.

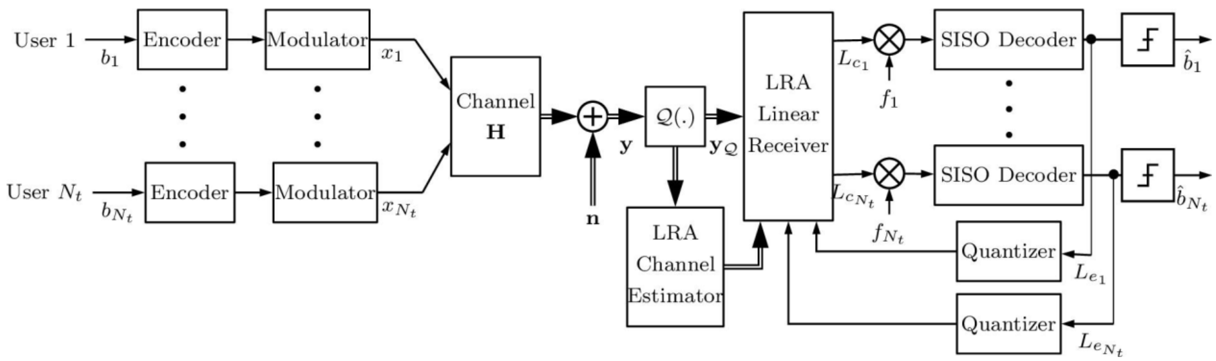


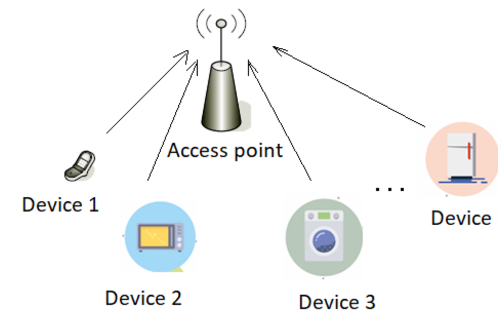
Energy-efficient channel estimation (3/3)

- We also assess the symbol error rate (SER) versus the SNR using a linear receive filter.
- The SER results show that oversampling-based channel estimation is energy-efficient and has a performance close to that of perfect channel estimation.
- The SER performance and the energy-efficiency can be further improved with channel coding and iterative processing.



Interference mitigation at the receiver (1/3)





- In most modern wireless systems, joint detection and decoding is key for interference mitigation
- However, with energy-efficient techniques special attention should be paid to coarsely quantized signals.
- Key mechanism : the soft information exchange between the detector and the channel decoder, which leads to successive performance improvement.
- Quantizers with adjustable scaling factors can avoid trapping sets of regular LDPC codes and refine the exchange of LLRs between the detector and the decoder.

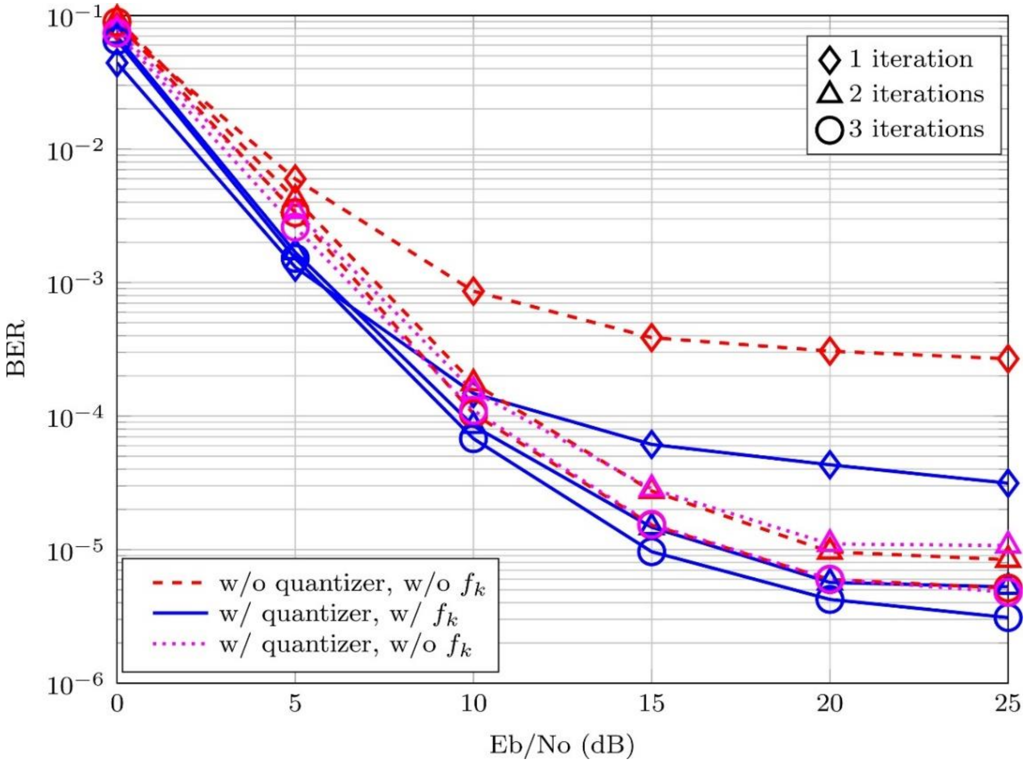
Z. Shao, R. C. de Lamare and L. T. N. Landau, "Iterative Detection and Decoding for Large-Scale Multiple-Antenna Systems With 1-Bit ADCs," in IEEE Wireless Communications Letters, vol. 7, no. 3, pp. 476-479, June 2018.

Interference mitigation at the receiver (2/3)

- We consider K = 12 single-antenna users, N_r = 32 antennas at the receive and 40 pilots.
- The model is given by

$$\boldsymbol{r} = \sum_{k=1}^{K} \boldsymbol{H}_k \boldsymbol{s}_k + \boldsymbol{n}$$

- Problem: to detect $\boldsymbol{s}_k$
- The system has a significant performance gain after 2 iterations.
- These results also demonstrate that the quantizer with the scaling factors offer extra performance gains.

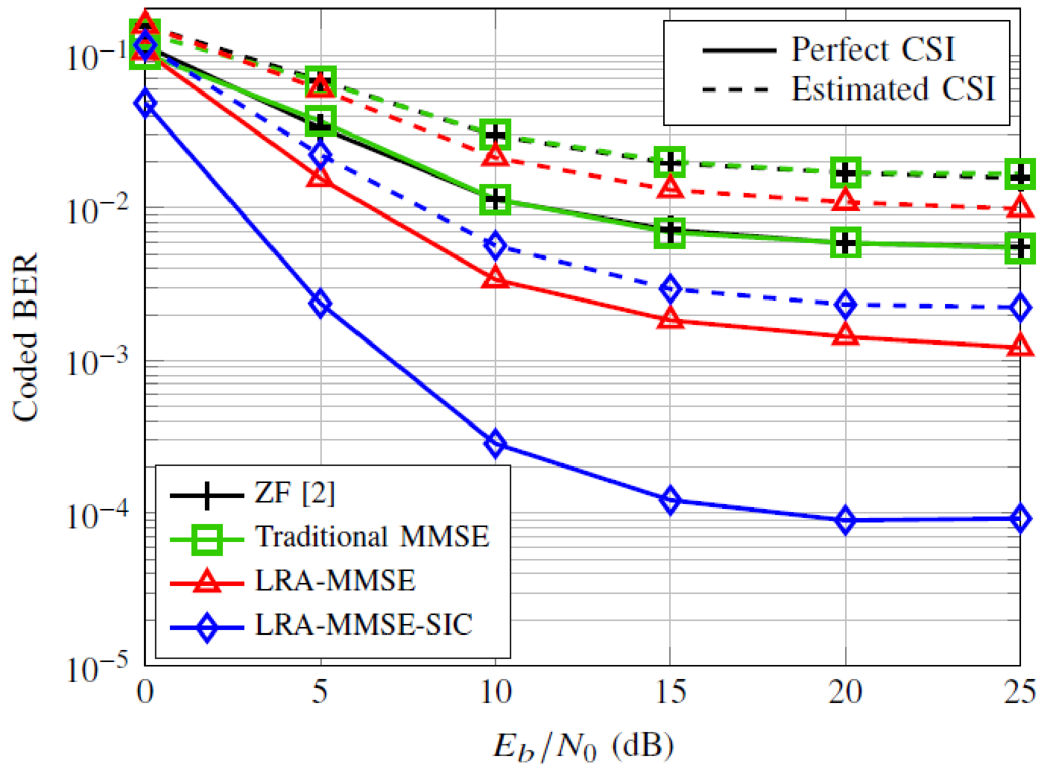


Interference mitigation at the receiver (3/3)

- We consider now K = 15 single-antenna users, N_r = 32 antennas at the receive, 3 iterations, linear and SIC techniques, and 40 pilots.

- We consider results with perfect CSI and estimated CSI.

- The system with successive interference cancellation and a LRA-MMSE receive filter has the best performance.



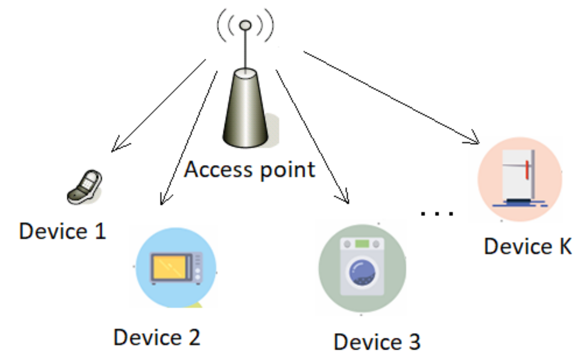
Interference mitigation at the transmitter (1/5)

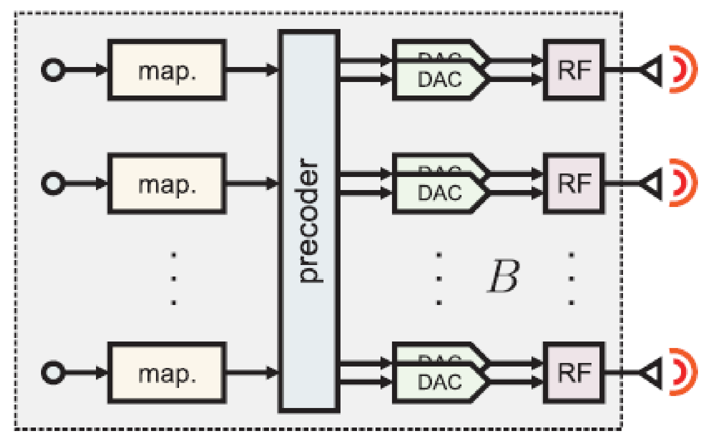
- Interference mitigation can be performed by transmit processing using precoding on the downlink, which requires channel state information.

- Key problem: to design a transformation that is applied to the transmit signal that cancels interference.

- An energy-efficient precoder employs coarse quantization (1-3 bits to represent each sample) in the DAC.

- This strategy can reduce the energy consumption and may also simplify the RF chain in the case of 1-bit solutions.





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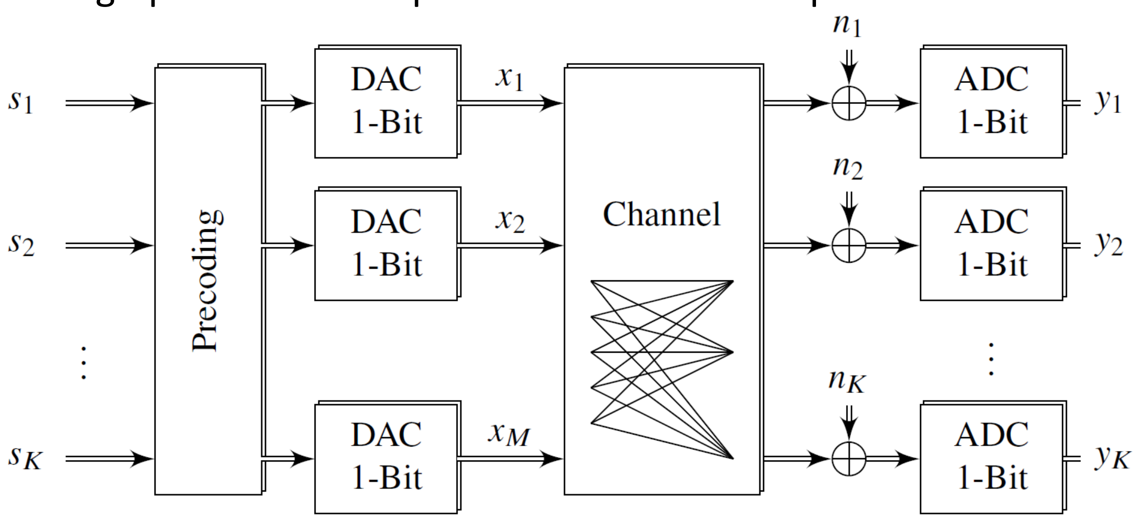
L. T. N. Landau and R. C. de Lamare, "Branch-and-Bound Precoding for Multiuser MIMO Systems With 1-Bit Quantization," in IEEE Wireless Communications Letters, vol. 6, no. 6, pp. 770-773, Dec. 2017.

Interference mitigation at the transmitter (2/5)

- We have recently developed a 1-bit optimal precoding technique that is a benchmark in the area.
- Each precoding operation corresponds to a numerical optimization.

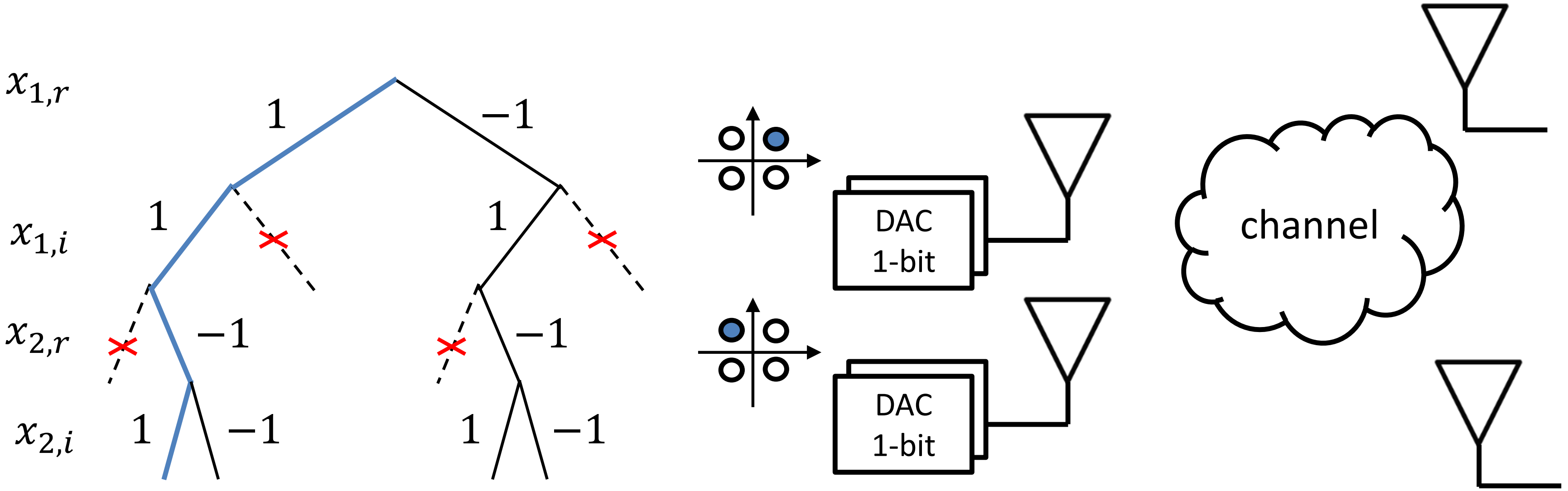


- Due to the DAC, the set of transmit symbols is discrete - > Non-convex optimization problem

L. Landau and R. de Lamare, "Branch-and-Bound Precoding for Multiuser MIMO Systems With 1-Bit Quantization," in *IEEE Wireless Communications Letters*, vol. 6, no. 6, pp. 770-773, Dec. *2017* .

Interference mitigation at the transmitter (3/5)

- Exhaustive search implies 2^{2M} different transmit symbols.
- The proposed Branch and Bound method can significantly reduce the number of candidates.
- Different design criteria: Max-Min-Distance to threshold, MSE , etc.



L. Landau and R. de Lamare, "Branch-and-Bound Precoding for Multiuser MIMO Systems With 1-Bit Quantization," in *IEEE Wireless Communications Letters*, vol. 6, no. 6, pp. 770-773, Dec. *2017* .

S. Jacobsson, W. Xu, G. Durisi and C. Studer, "MSE-Optimal 1-Bit Precoding for Multiuser MIMO Via Branch and Bound," *2018 IEEE Int. Conf. Acoust., Speech, Signal Process. (ICASSP)*, Calgary, AB, 2018, pp. 3589-3593.

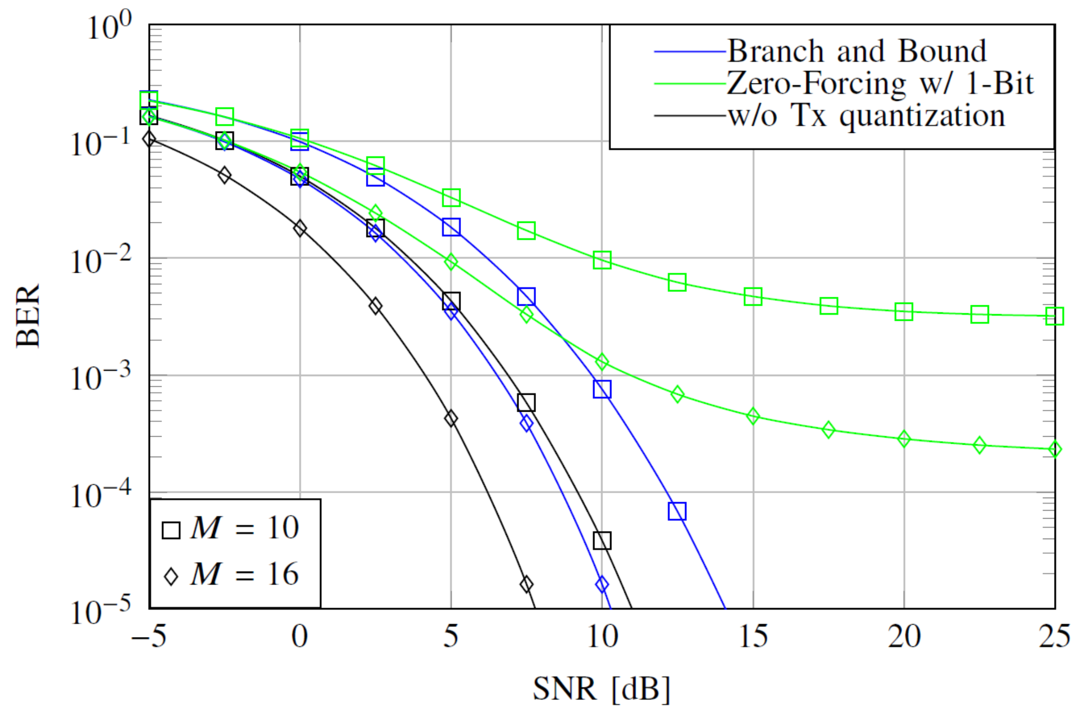
Interference mitigation at the transmitter (4/5)

- We consider M =10, 16 transmit antennas $K = 2$ users with single antennas and 1-bit ADCs at the receiver.

- The proposed optimal Branch-and-Bound precoding algorithm maximizes the minimum distance to the decision thresholds at the receivers.

- The optimal optimal Branch-and-Bound precoder outperforms linear precoding with rounding.

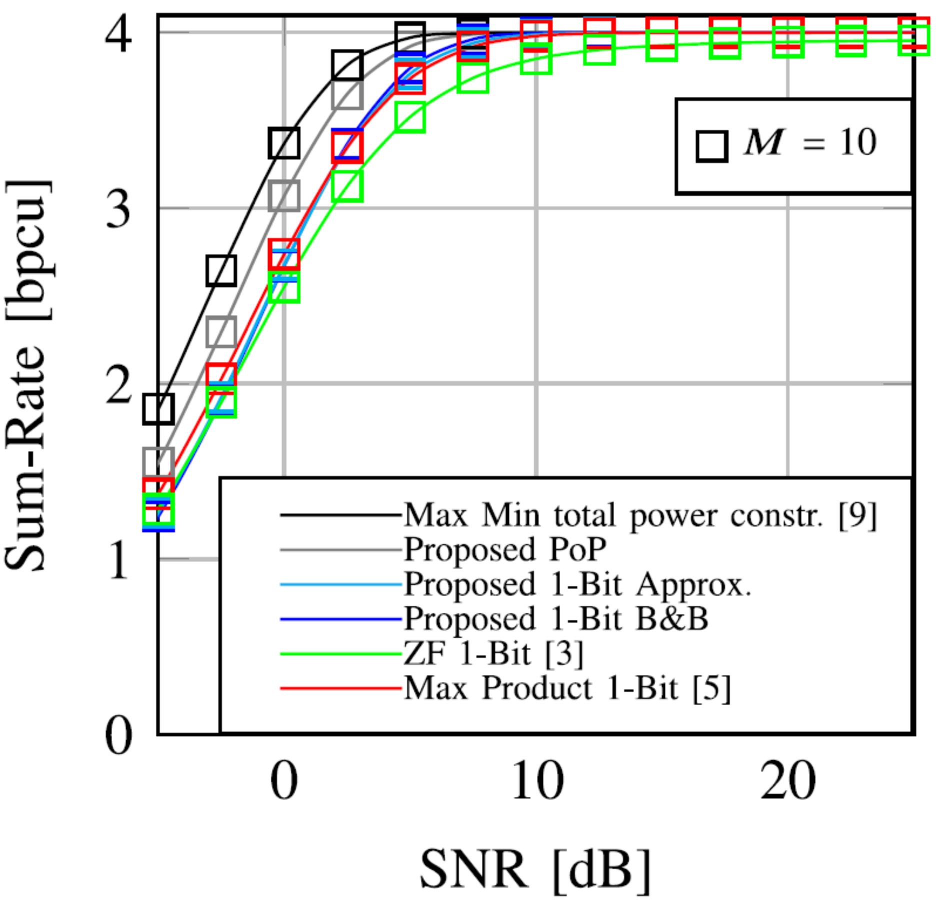
- We end up with less than 3dB loss in comparison to full resolution Tx



Interference mitigation at the transmitter (5/5)

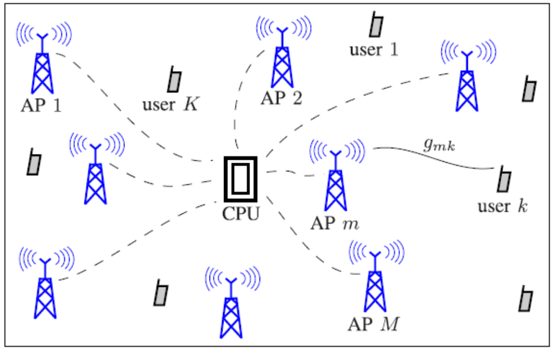
- We consider a system with $M = 10$ transmit antennas and $K = 2$ users with single-antenna receivers and 1-bit ADCs at the receiver.

- The proposed optimal Branch-and-Bound, PoP and 1bit approx. precoding algorithms obtain a sum-rate performance close to that of capacity (Max-Min total power constr.)



Ongoing and future work

- Joint design of AGC and receive processing
- Energy-efficient decoding algorithms and compensation strategies for LLRs
- Nonlinear precoding with arbitrary number of bits
- Dynamic oversampling strategies
- Energy-efficient network architectures
  - Distributed antenna systems and cell-free concepts
  - Topology adaptation and antenna selection



H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson and T. L. Marzetta, "Cell-Free Massive MIMO Versus Small Cells," in IEEE Transactions on Wireless Communications, vol. 16, no. 3, pp. 1834-1850, March 2017

Conclusions

- We have presented energy-efficient design concepts and algorithm for 5G cellular and IoT networks.
- Energy-efficient approaches are likely to dominate the wireless communications scenarios in the next decade or so.
- This is because the energy consumption of wireless networks to date are unsustainable and must be deal with to prevent serious issues in energy supple and costs.
- Energy-efficient approaches rely on using coarsely quantized signals, i.e., signals represented with as few bits as possible because they take the biggest share of energy consumption.
- Novel network architectures such as distributed antenna and cell-free systems and protocols will also be key to reducing the energy consumption.

Questions?