MPDQ-Based High-Order QAM Detection Scheme for Massive MIMO with Low-Precision Quantization

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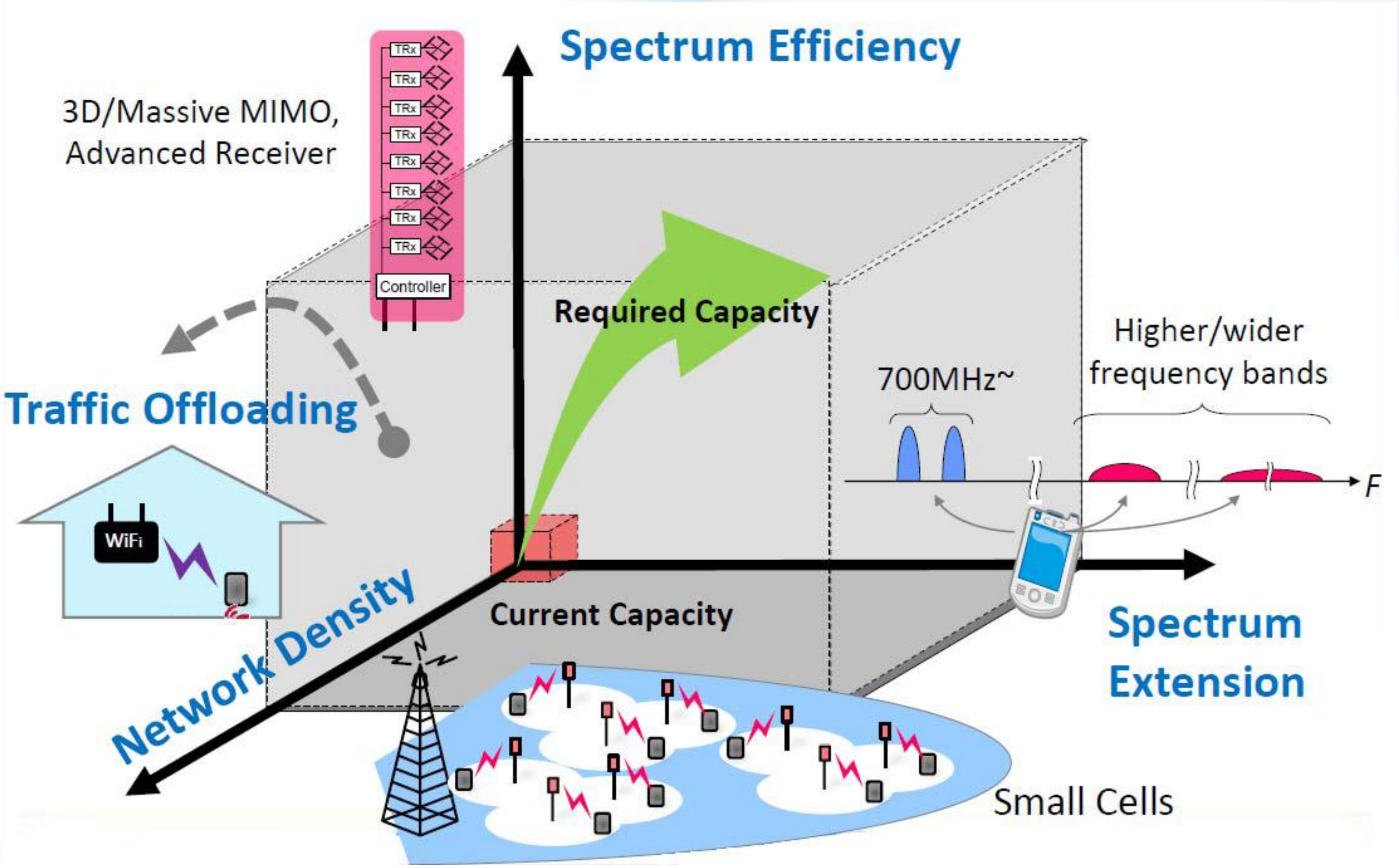
Background of 5G

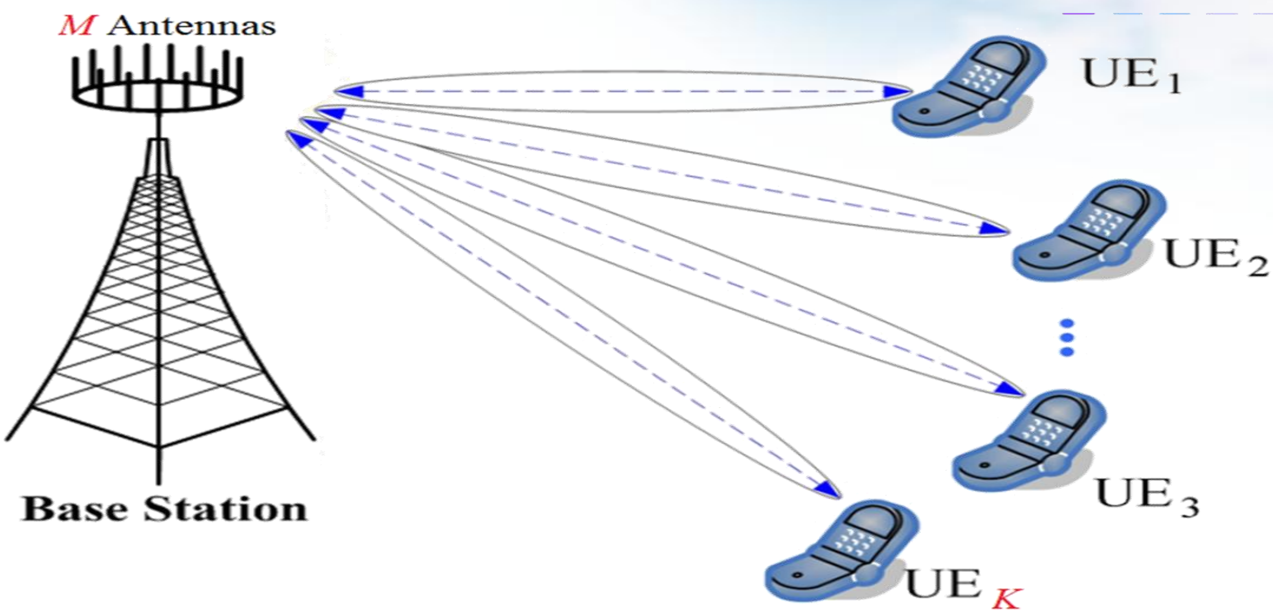
- Key requirement: 1000 folds of increase in data traffic
- Three main directions



Massive MIMO

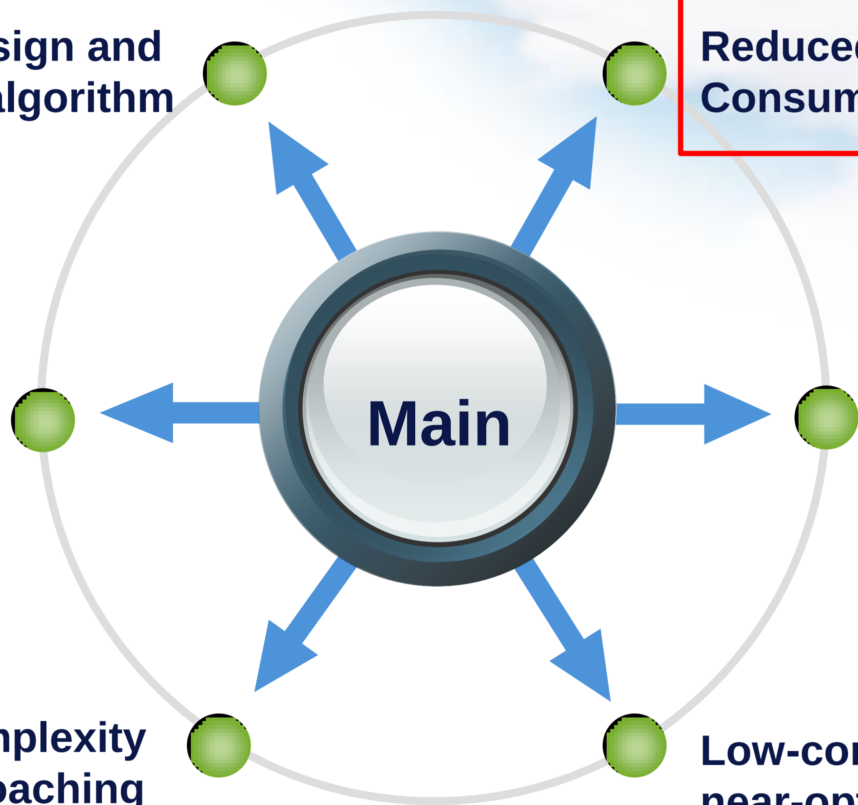
❖ What is massive MIMO and why ?

- Use hundreds of antennas at the BS to simultaneously serve a set of users
- Increase the spectral and energy efficiency by orders of magnitude



F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta and O. Edfors, "Scaling up MIMO: Opportunities and challenges with very large arrays," *IEEE Signal Processing Magazine,* vol.30, pp.40-60, 2013.

Challenges



- Efficient Pilot design and channel estimation algorithm
- Reduced power Consumption of RF chains
- Efficient channel feedback method
- Capacity enhancement in the uplink
- Low-complexity capacity-approaching precoding algorithm
- Low-complexity near-optimal signal detection algorithm

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Motivation

high throughput → high-order QAM

↓

reliable detection → high-precision ADC

↓

required by each RF chains

↓

power consumption is unaffordable

Motivation

existing detector

ML detector is optimal → complexity increases exponentially

MMSE is suboptimal → suffers from the matrix inversion

SD is near-optimal → cannot deal with the high-order QAM

What is more , all of them dealing with high-order QAM need 12-16 bits to achieve acceptable performance

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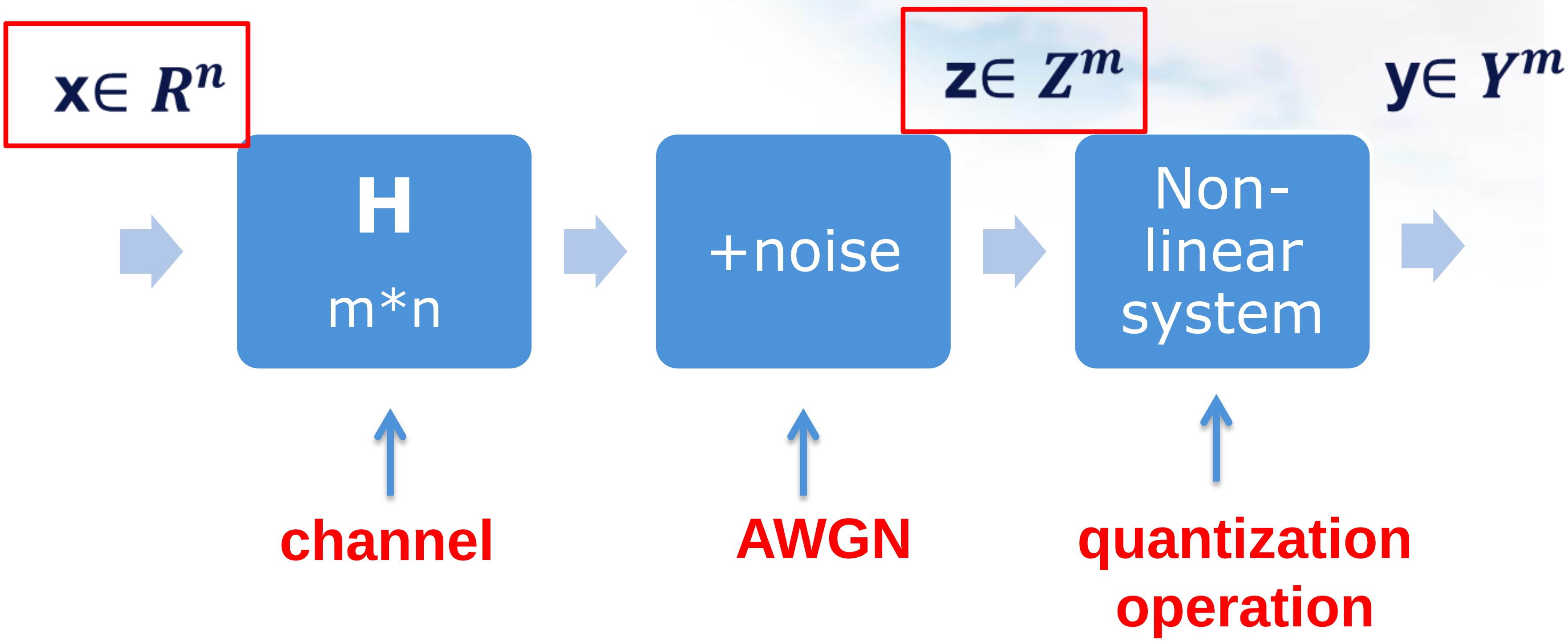
System Model



System Model

- $\boldsymbol{Q}(\bullet)$ is the quantization operation

$$\mathbf{Y}=\boldsymbol{Q}(\mathbf{HX}+\mathbf{N})$$

- b-bit uniform quantizer. $\boldsymbol{Q}(\bullet)$ is defined as

$$r = \boldsymbol{Q}(c) = \begin{cases} \boldsymbol{sign}(c) \cdot \left(\left[\frac{c}{\Delta} \right] \Delta + \frac{\Delta}{2} \right) , & |c| < G + \frac{\Delta}{2} \\ \boldsymbol{sign}(c) \cdot G \ , & |c| \geq G + \frac{\Delta}{2} \\ \frac{\Delta}{2} \ , & c = 0 \end{cases}$$

where $\Delta = \max(\mathbf{C})/2^{b-1}$ is quantization step, and $G=([|\max(\mathbf{C})|/\Delta])$ is saturation level.

- the upper and lower quantitative bounds for further detection:

$$B_{up}(r) = \begin{cases} +\infty , & \text{if } r = G \\ r + \frac{\Delta}{2} , & otherwise \end{cases}$$

$$B_{low}(r) = \begin{cases} -\infty , & \text{if } r = -G \\ r - \frac{\Delta}{2} & otherwise \end{cases}$$

Estimation method

The approximate marginal distribution is calculated as

$$\hat{p}^{t}_{x_j|Y}(x_j|Y) \propto p_x(x_j) \prod_{i=1}^{2N_r} m^{t}_{z_i \to x_j}(x_j).$$

Finally, the estimate $\hat{X}$ is computed as

$$\hat{x}^{t}_{j} = \int x \hat{p}^{t}_{x_j|Y}(x_j|Y) dx$$

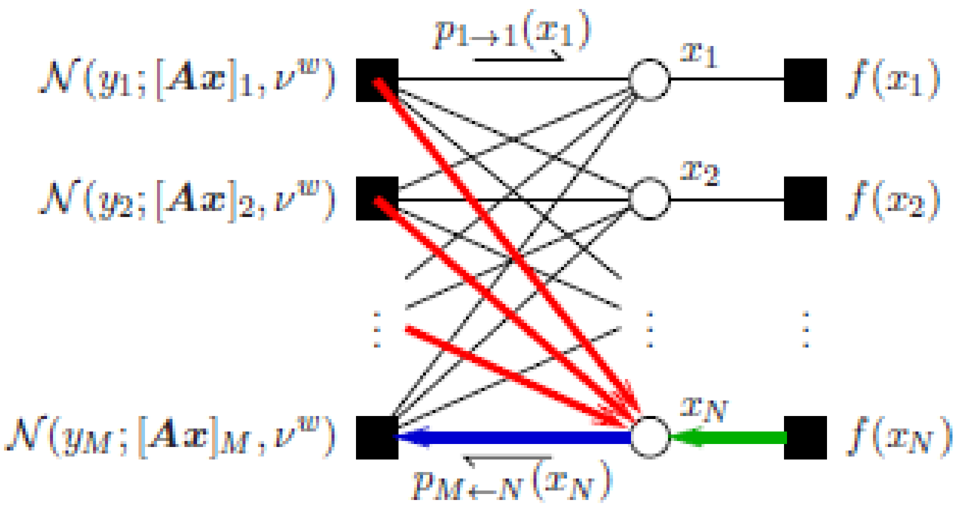
In message passing algorithm, the messages are calculated as

$$m^{t}_{y_i \leftarrow x_j}(x_j) \propto p_x \prod_{l \neq j} m^{t}_{y_l \to x_j}(x_j) \,,$$

$$m^{t}_{y_i \to x_j}(x_j) \propto \int p_{y|hx} \prod_{k \neq j} m^{t-1}_{y_i \leftarrow x_k}(x_j) dx_{\setminus j} \,,$$

The factor-graph representation

- Here , approximated message passing algorithm is exploited to iteratively estimate the unknown vector.



- In Massive MIMO systems, the messages sent between the transceiver nodes are assumed to approximately Gaussian distributed.
- Therefore can be calculated by their first and second order of statistical properties, i.e. the expectation and the variance.

MPDQ-hl algorithm

- But in traditional message passing algorithm , the observation vector Y is obtained directly.
- In our scheme , Y is observed after *b* bit quantization, so we proposed a method to estimate the vector Z before the quantization, the expression are as follows:

$$\hat{p}_i^t = \sum_j h_{ij}\hat{x}_i^t - vp_i^t\hat{y}_i^{t-1} ,$$

$$vp_i^t = \sum_j h_{ij}^2 vx_i^{t-1}$$

$$\hat{z}_i^t = \frac{1}{vp_i^t+\sigma^2}(\mathrm{E}[u_i|u_i \in q^{-1}(y_i)] - \hat{p}_i^t) ,$$

$$vz_i^t = \frac{1}{vp_i^t+\sigma^2}\left(1 - \frac{\mathrm{Var}[u_i|u_i \in q^{-1}(y_i)]}{vp_i^t+\sigma^2}\right) ,$$

where the expectation and the variance are evaluated with respect to $u_i \sim N(\hat{p}_i^t, vp_i^t + \sigma^2)$.

$$q^{-1}(y_i) = [B_{low}(y_i), B_{up}(y_i)].$$

MPDQ-hl algorithm

- Given the prior information p_x, the received measurement signal Y, the channel state information H, the noise variance σ^2, and the mapping q of the quantizer Q(•), the estimation of X is shown below.

$$\hat{r}_j^t = \hat{x}_j^{t-1} + vr_j^t \sum_i h_{ij}\, \hat{z}_i^t \,,$$

$$vr_j^t = \left[\sum_i h_{ij}^2 vz_i^t\right]^{-1} ,$$

$$\hat{x}_j^t = \mathrm{E}[\mathrm{x} \mid \hat{r}_j^t, vr_j^t\,] \,,$$

$$vx_j^t = \mathrm{Var}[\mathrm{x} \mid \hat{r}_j^t, vr_j^t] \,,$$

where the expectation and the variance are evaluated with respect to p(x| $\hat{r}_j^t, vr_j^t$) ∝ N(x; $\hat{r}_j^t, vr_j^t$)p_x(•).

Complexity Analysis

- The MPDQ-hl algorithm is perfect dealing with non-linear system, so is suitable for quantization problem, we exploit it for low-precision problem.
- The proposed algorithm reduces the complexity with just matrix multiplication.
- The complexity of the proposed scheme is proved to be one order of magnitude smaller than that of conventional MMSE.
- Its rapid convergence property is analyzed by MSE.

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Experimental Results

Simulation parameters:

- 256-QAM is utilized in the system.
- The data size L is 300.
- the iterative termination parameter *tol* is set as 10^{-3}.
- The number of trials for each Monte Carlo simulation is 1000 times.
- The proposed algorithm is compared with quantized MMSE (qMMSE) and unquantized MMSE.

Experimental Results

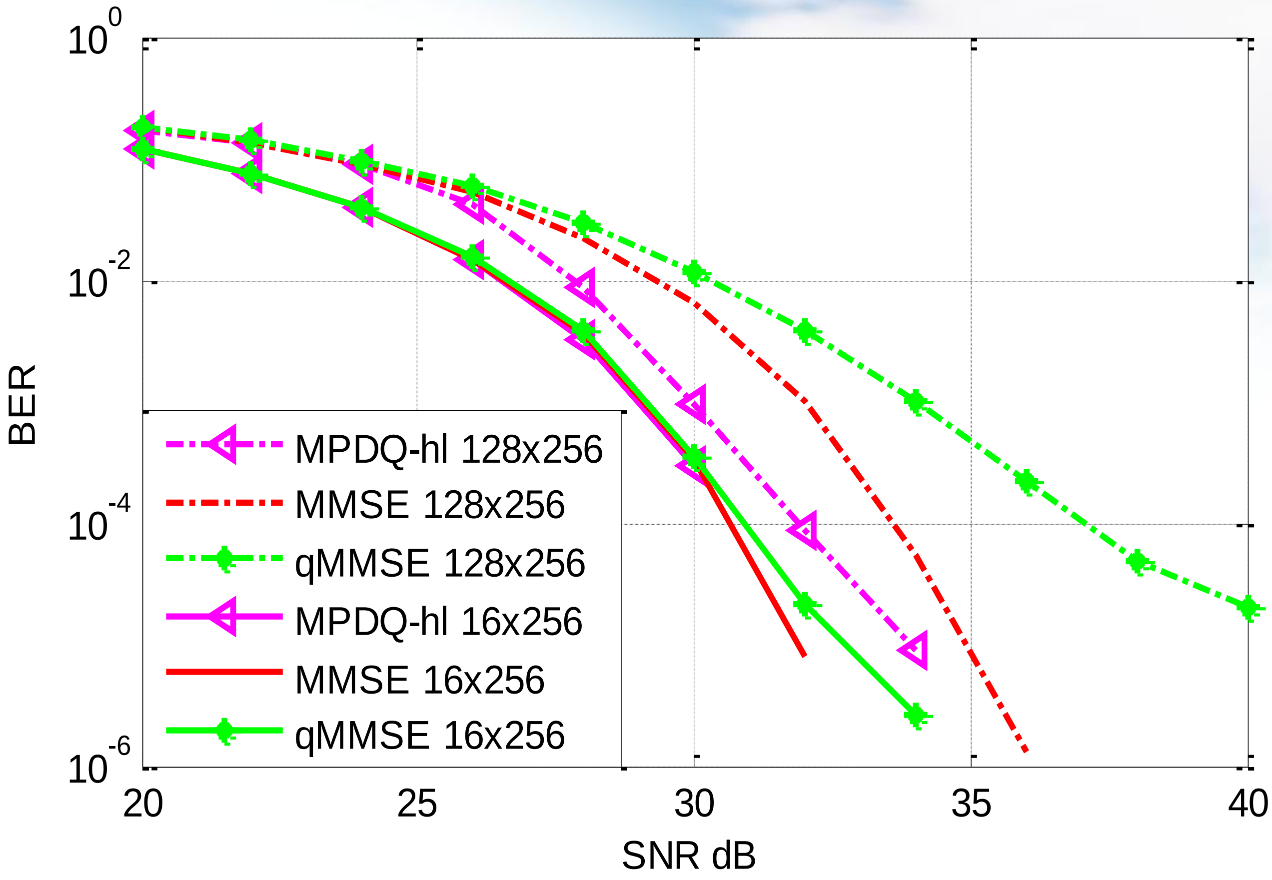

Fig. 1. 7 bits quantization with different MIMO configurations M×N

Experimental Results

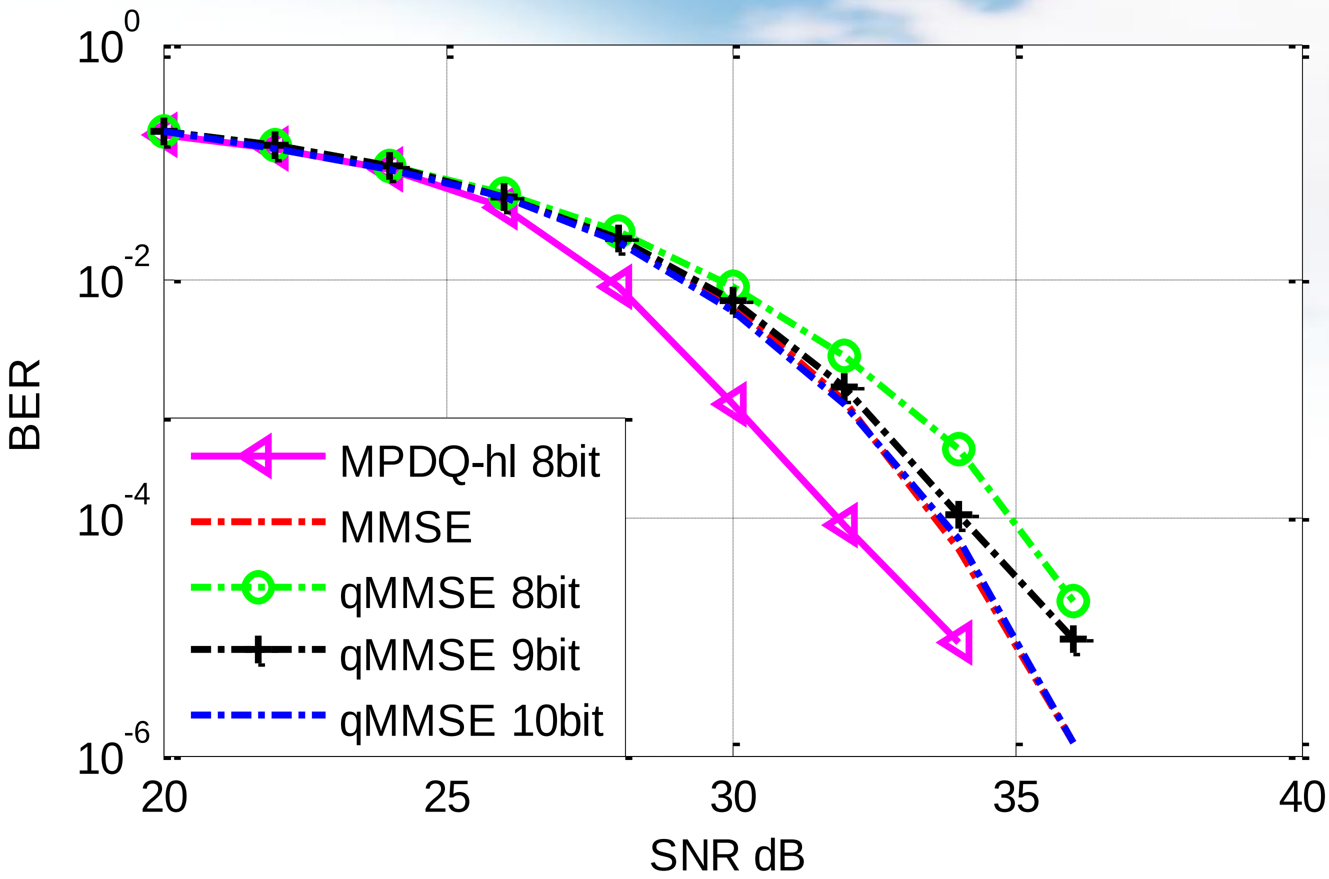

Fig. 2. 128×256 MIMO with different quantization bits

Experimental Results

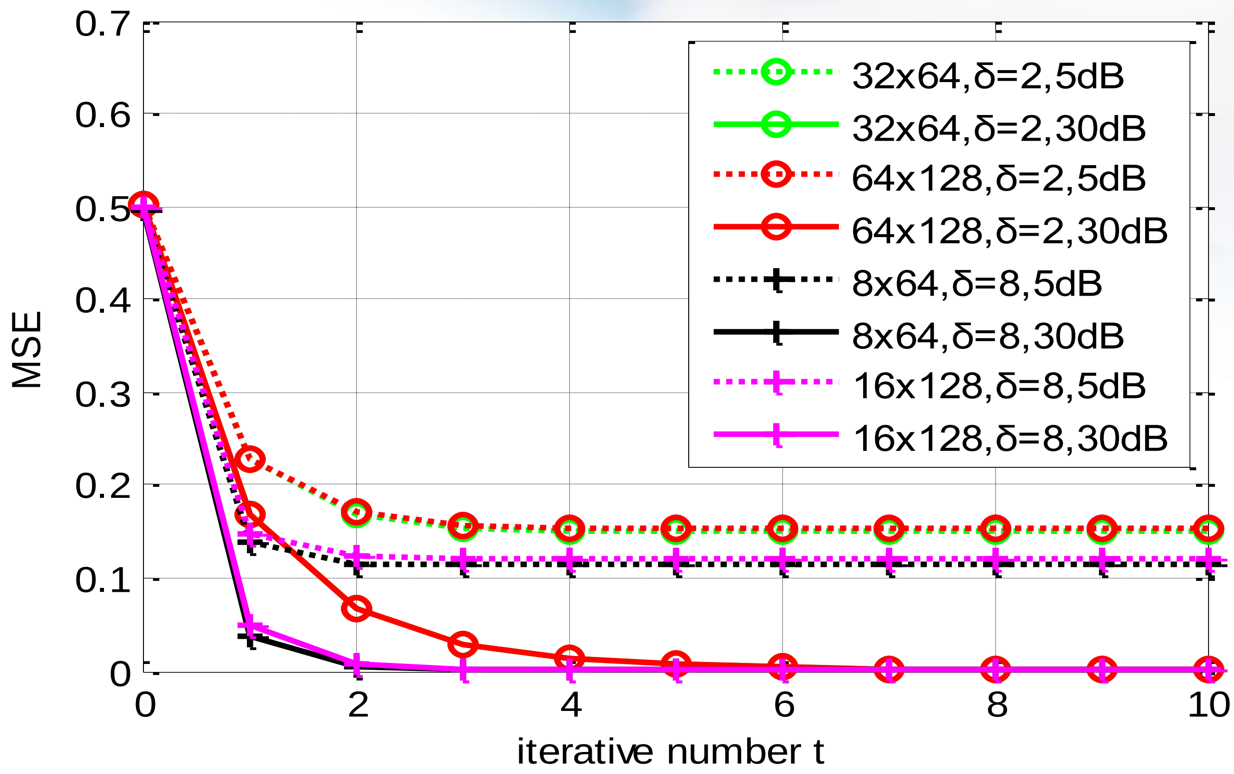

Fig. 3. MSE at each iteration with different MIMO parameters

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Conclusion

- In this paper, we have proposed the MPDQ-hl algorithm to detect high-order QAM signals for massive MIMO systems with low-precision quantization.
- In 256-QAM systems, simulation results show that MPDQ-hl with 7 bits quantization could achieve better BER performance than MMSE with full precision system, thus saving 3 bits or more by comparison.
- Compared with the conventional MMSE algorithm with the complexity of O(N^3), the complexity of MPDQ-hl can be reduced to O(N^2), where N is the number of transmitting antennas.
- Its rapid convergence property is analyzed by MSE.
- It can reduce the power consumption in Massive MIMO systems.

Thank You !