Digital baseband algorithmic and architectural solutions to master complexity

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Massive number of antenna elements

... Leads to

Increased MIMO processing complexity

More antenna tranceiver units

More data to stored and send between transceivers and baseband processing units

1. What can be done to make MIMO processing more computational efficient?
2. How can digital baseband processing relax the requirement on analog compoments?
3. How can we handle the massive data storage?

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Efficient precoding and detection architecture and circuitries

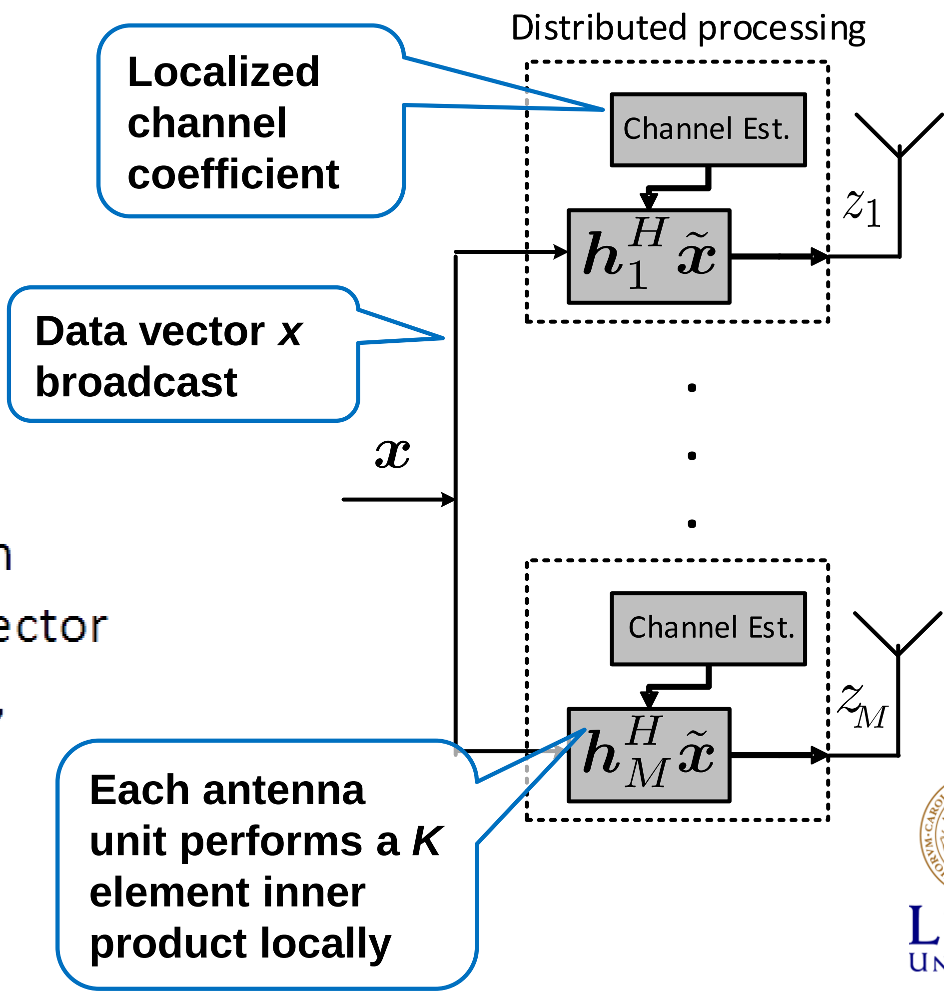
Distributed architecture for MRT

MRT precoder

$$\boldsymbol{W} = \boldsymbol{H}^H = \begin{bmatrix} \boldsymbol{h}_1^H \\ \boldsymbol{h}_2^H \\ \vdots \\ \boldsymbol{h}_M^H \end{bmatrix}$$

Row *m* contains the Hermitian transpose of the coefficient vector from antenna *m* to all *K* users,

$$\boldsymbol{h}_m^H = [h_{1,m}^* \ldots h_{K,m}^*]$$

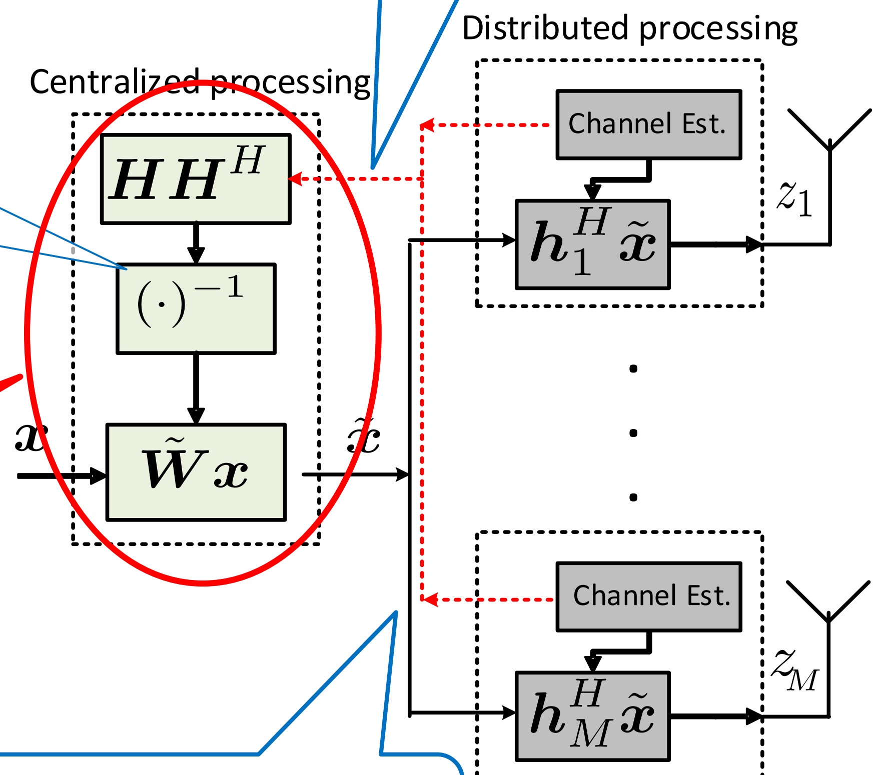


Hybrid architecture for ZF precoding

$$H^{\dagger} = H^{H}(HH^{H})^{-1}$$

Collect channel estimation

$(HH^{H})^{-1}$ calculated once per channel update

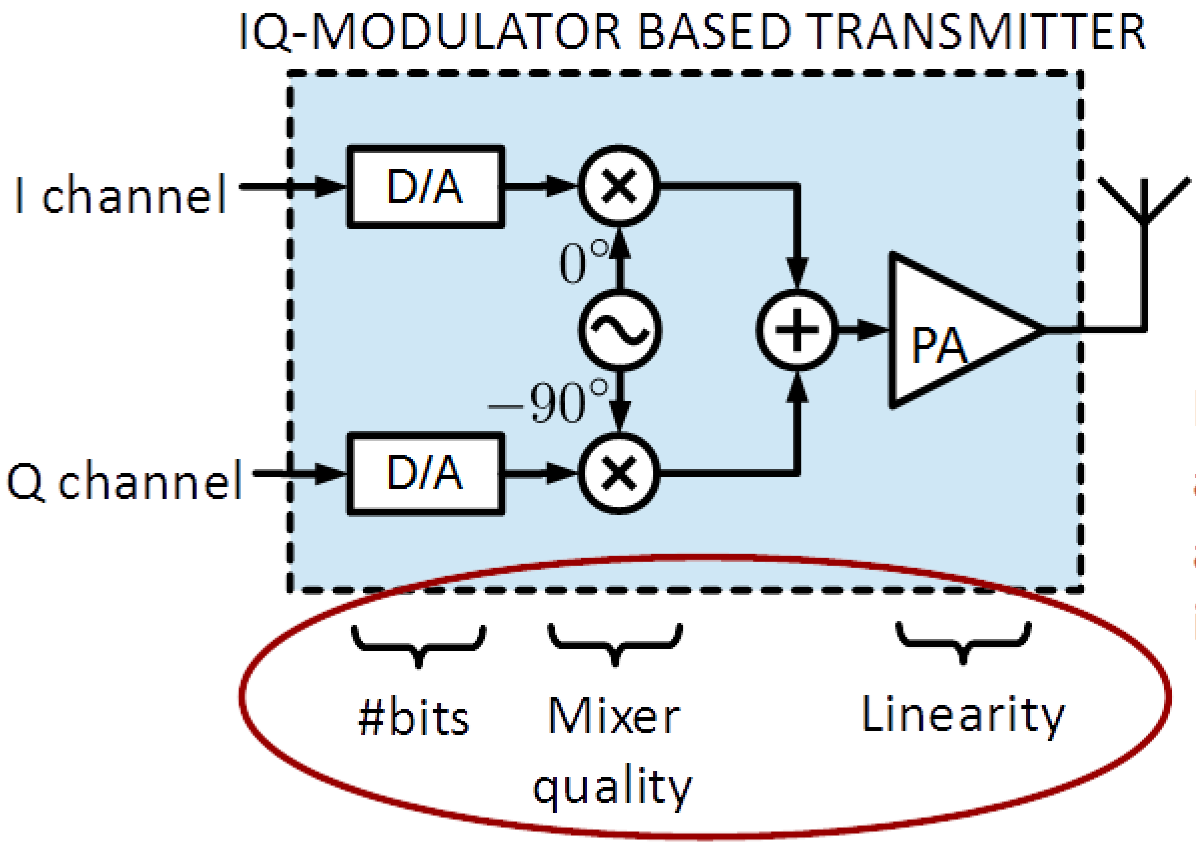


How can we implement this efficiently?

Same as MRT, local match filtering

DSP assistants the use of low-cost analog components

Enable low-cost analog components



Keep these as low as possible to make antenna units inexpensive

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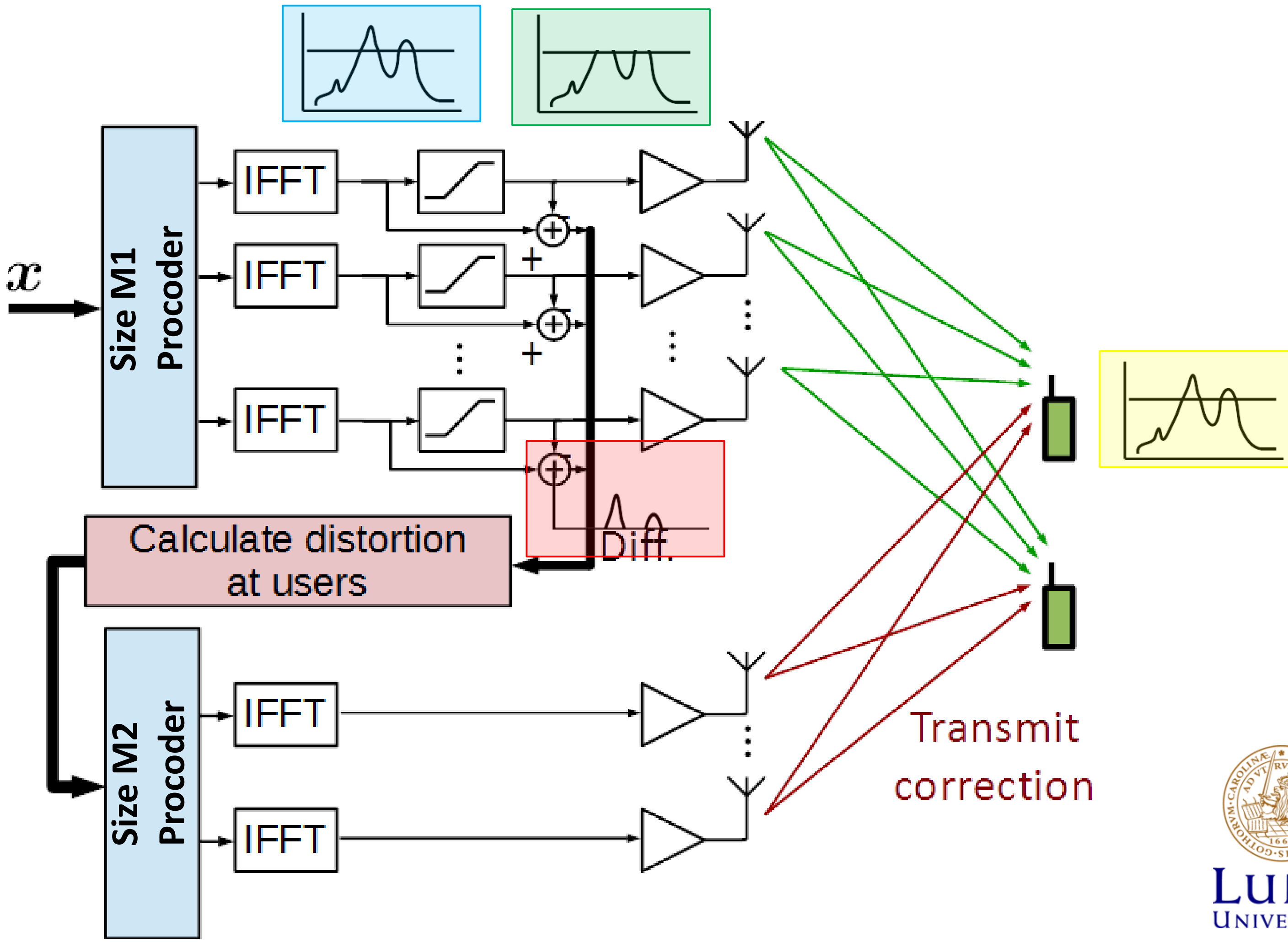
Reducing PA dynamic range with antenna reservation (concept)



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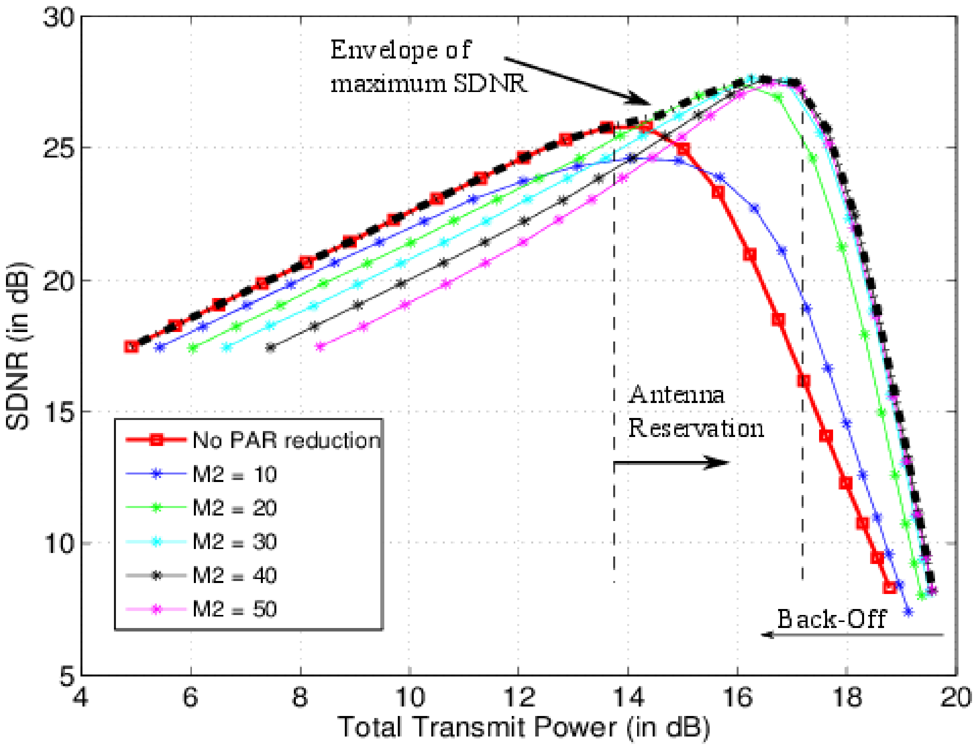
Reducing PA dynamic range with antenna reservation (performance)



# of User (K) = 10,
# of antennas (M) = 100
M2 – Reserved Antennas
1W Hard Saturation PAs

Implementation: Reserving 20 of 100 antennas with 10 users reduces PA back-off by **3-4 dB** at a cost of only **15%** increase in precoding complexity (comparing to QRD-based ZF precoder)

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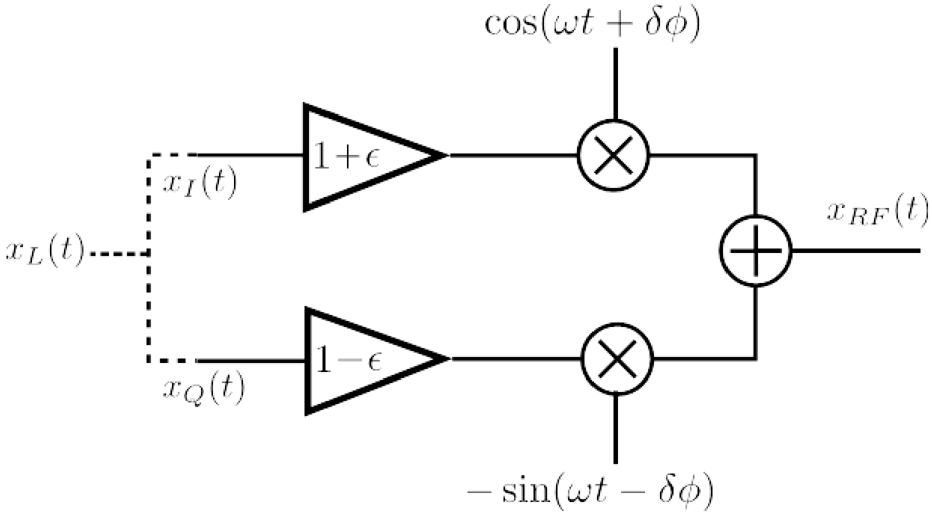
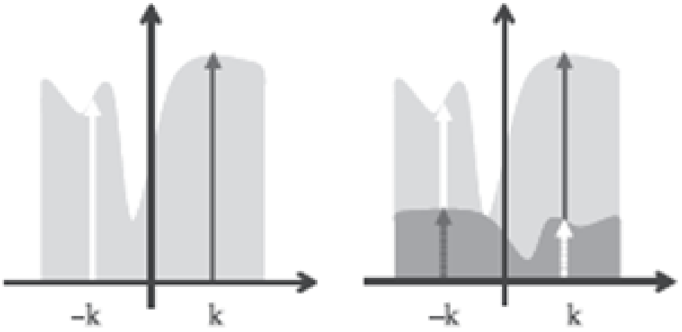
Compensating IQ-imbalance (system model)

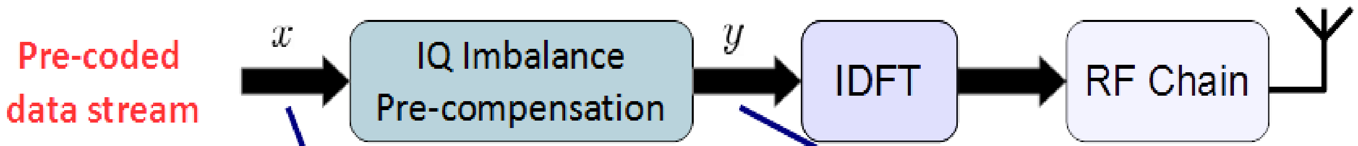




Assuming perfect receiver (Rx) chain

$$X_{Rx}(f) = aX_L(f) + bX_L^*(-f)$$

Compensating IQ-imbalance (scheme)



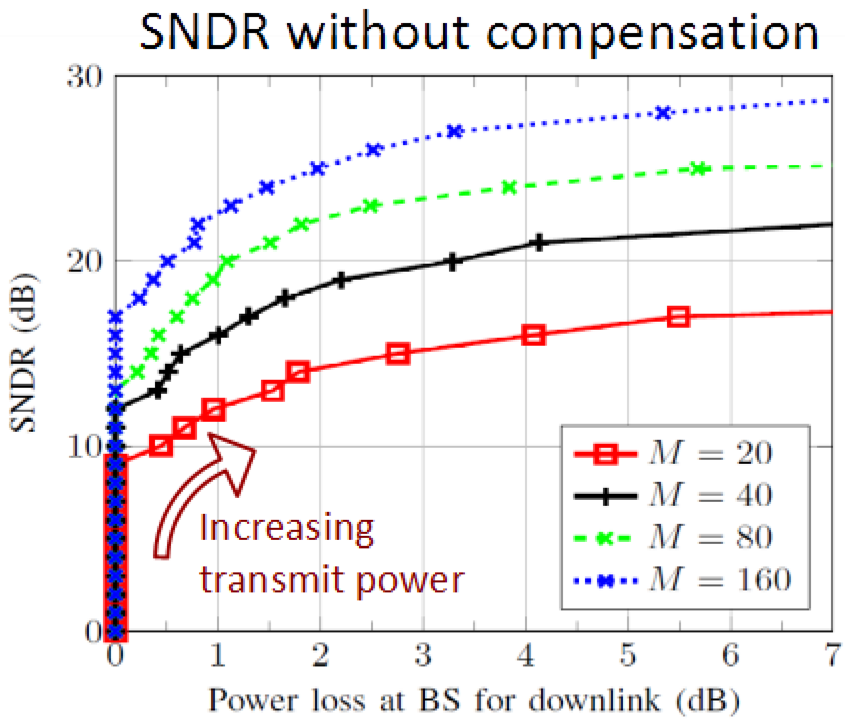
$$\begin{bmatrix} x_r^n \\ x_i^n \\ x_r^{N-n} \\ x_i^{N-n} \end{bmatrix} = \begin{bmatrix} a_r^n & -a_i & b_r^{N-n} & b_i^{N-n} \\ a_i^n & a_r & b_i^{N-n} & -b_r^{N-n} \\ b_r^n & b_i & a_r^{N-n} & -a_i^{N-n} \\ b_i^n & -b_r & a_i^{N-n} & a_r^{N-n} \end{bmatrix} \begin{bmatrix} y_r^n \\ y_i^n \\ y_r^{N-n} \\ y_i^{N-n} \end{bmatrix}$$

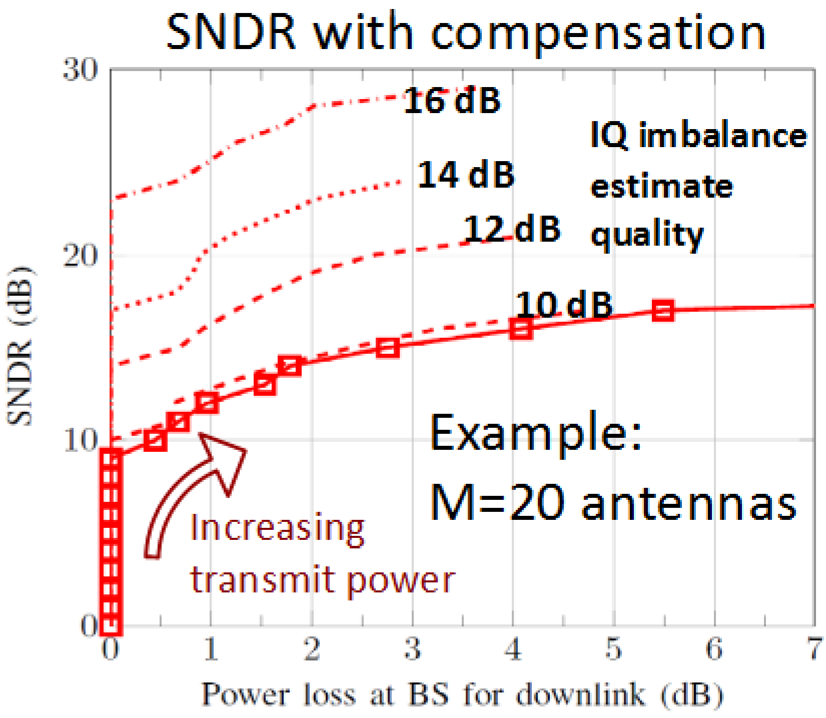
Item	Value
Process	ST 28nm
Power	0.61mW
Latency	2clk @ 200MHz
Gate count	24k

One instance per antenna

Large diagonal elements. Can be efficiently implemented as a **Jacobi iterative solver**

Compensating IQ-imbalance (result)

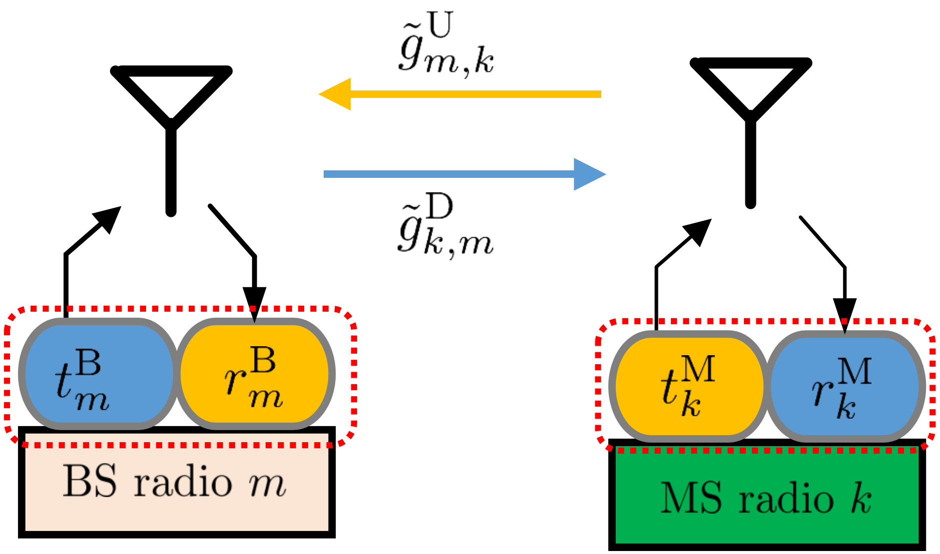




Simulated IQ imbalance with mean value
6% amplitude and 6 degree phase imbalance
(random on antennas)

Reciprocity calibration (system model)

- Channel reciprocity is used to realize efficient TDD Massive MIMO



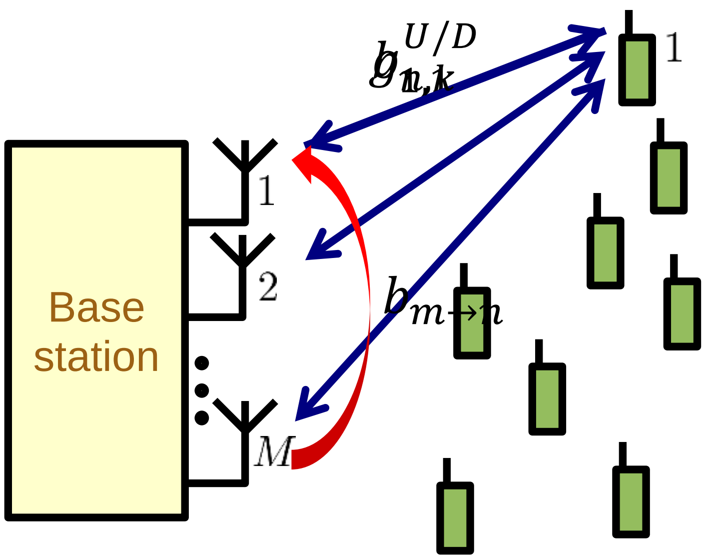
$$g^{\mathrm{U}}_{m,k} = r^{\mathrm{B}}_{m}\,\tilde{g}^{\mathrm{U}}_{m,k}\,t^{\mathrm{M}}_{k}$$

$$g^{\mathrm{D}}_{k,m} = r^{\mathrm{M}}_{k}\,\tilde{g}^{\mathrm{D}}_{k,m}\,t^{\mathrm{B}}_{m},$$

$$b_{m,k} = \frac{t^{\mathrm{B}}_{m}}{r^{\mathrm{B}}_{m}}\,\frac{r^{\mathrm{M}}_{k}}{t^{\mathrm{M}}_{k}}$$

Reciprocity calibration (scheme)

- Calibrate by refering to the same base-station antenna
  - Calibration within base-station
  - Use antenna coupling for the estimation



Calibration between reference ante. and UE: **down-link pilot**

$$b_{m,k} = \frac{t_m^{\mathrm{B}}}{r_m^{\mathrm{B}}}\,\frac{r_k^{\mathrm{M}}}{t_k^{\mathrm{M}}} = \boxed{\frac{r_n^{\mathrm{B}}\,t_m^{\mathrm{B}}}{r_m^{\mathrm{B}}\,t_n^{\mathrm{B}}}}\;\boxed{\frac{r_k^{\mathrm{M}}\,t_n^{\mathrm{B}}}{r_n^{\mathrm{B}}\,t_k^{\mathrm{M}}}} = b_{m\to n}\,b_{n,k}$$

Calibration with in base station: **slow changes**

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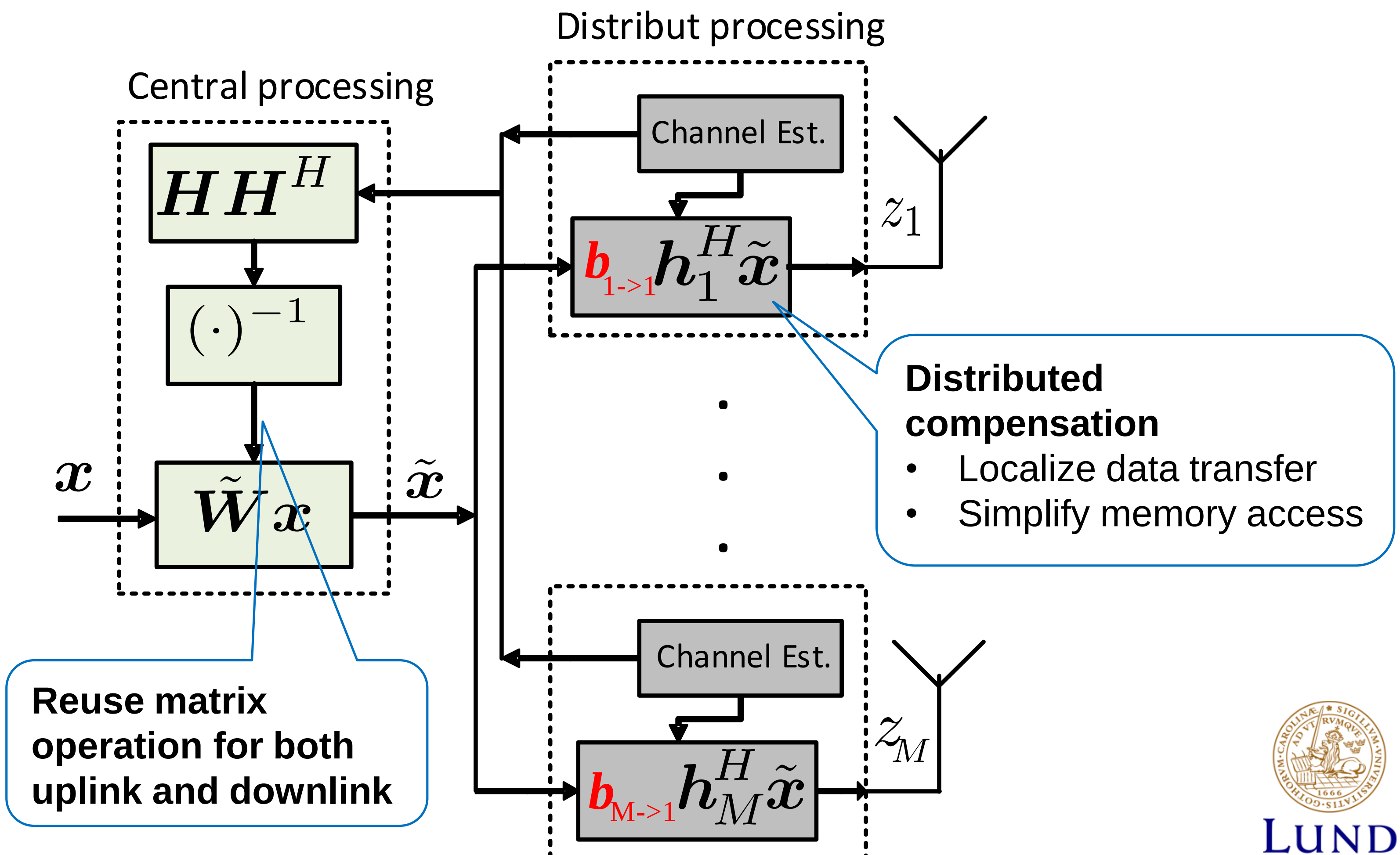
Reciprocity calibration (processing distribution)



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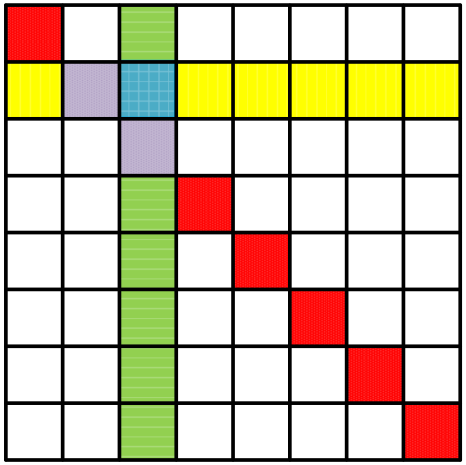
Parallel memory for channel matrix storage

Memory subsystem in Massive MIMO

- High capacity and throughput
  - Storage v.s. processing (150 subcarriers)

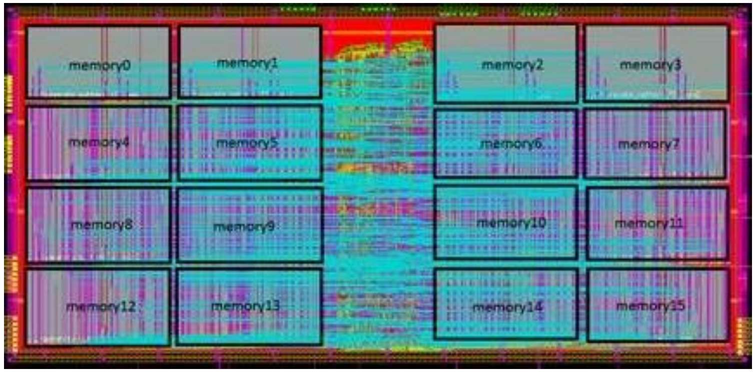
Channel matrix Memory	QRD-based ZF precoder
$0.28mm^2$	$0.13mm^2$

- Multiple access patterns
  - Column wise: $\boldsymbol{H}^H\boldsymbol{H}$
  - Row wise: $\boldsymbol{Hy}$
  - Diagonal wise: $\boldsymbol{H}^H\boldsymbol{H}+\alpha\boldsymbol{I}$
- Adjustable operand matrix size

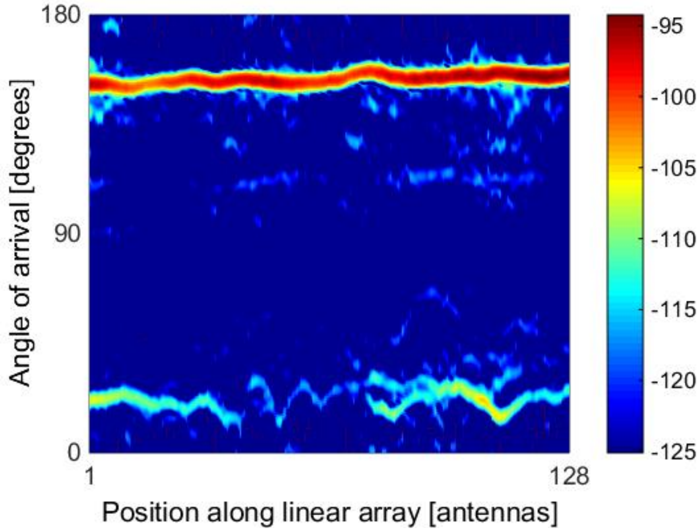


Hardware implementation of a 16-bank parallel memory

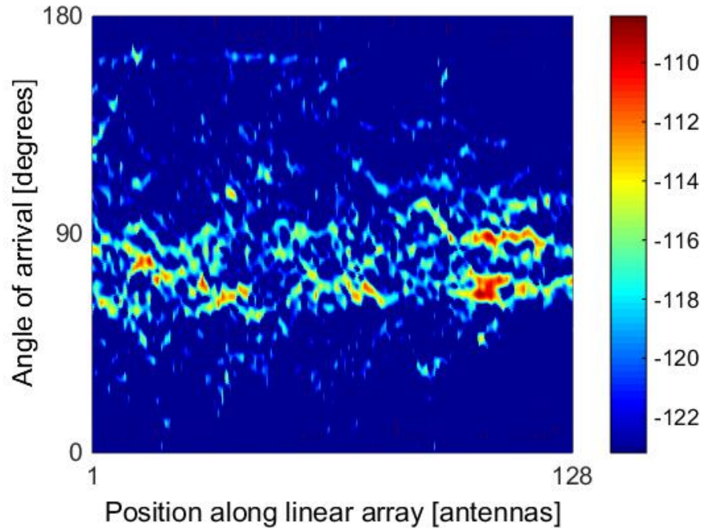
- Capacity 128kB: 15 subcarriers of 128×16 MIMO system
- Row/Column/Diagonal (16 elements) access in one clock cycle
- 0.28 mm^2 in ST 28nm technique
- 64 GB/s Throughput@1 GHz Frequency
- Power consumption
    - 197mW @write
    - 246mW @fetch



Exploiting the sparsity in massive MIMO channel



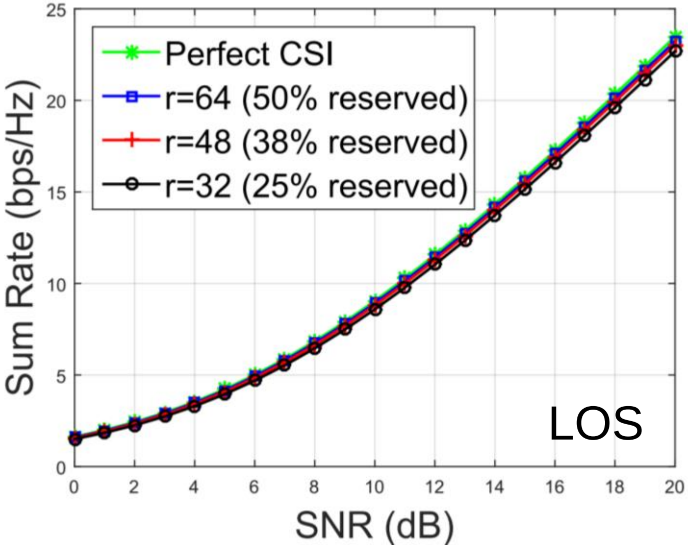
LOS scenario

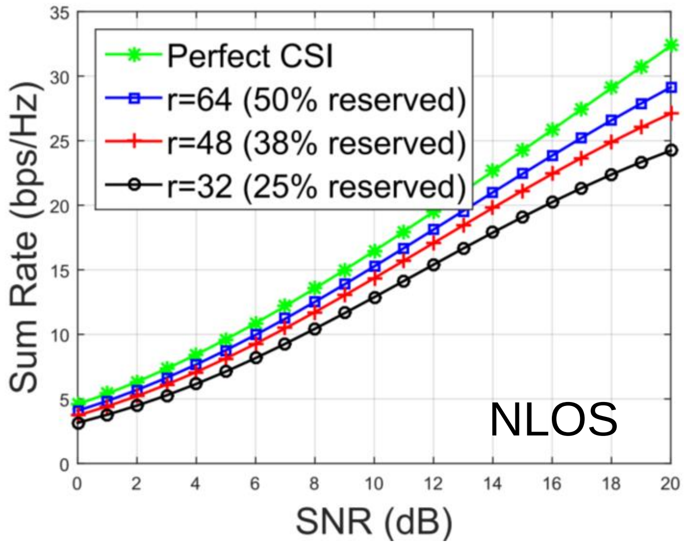


NLOS scenario

Distribution of angle of arrival signals at base station
(Real measured result with linear array of 128 antenna elements)

FFT-based channel data compression





Conclusions

- Efficient MIMO processing using massive MIMO properties
- DSP enables low-cost analog components
- Memory is crucial to achieve energy- and area- efficient baseband processing