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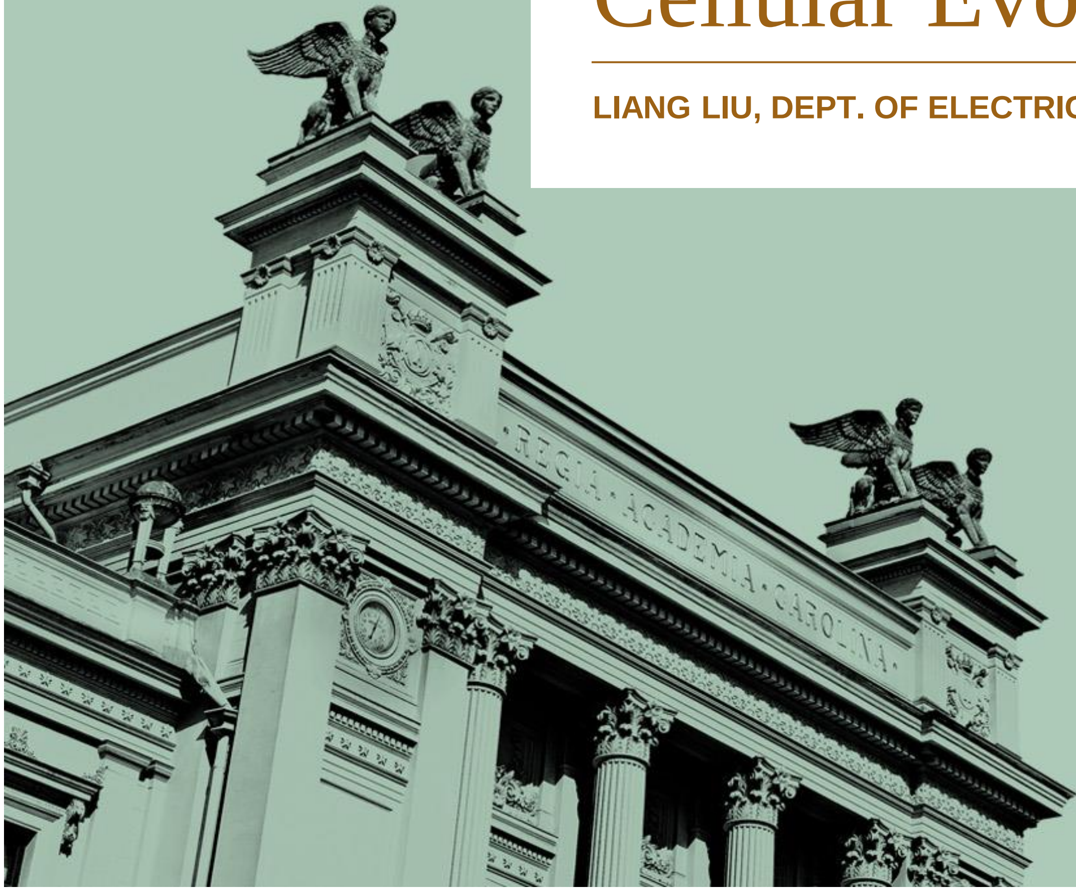
Baseband Processing for Cellular Evolution

LIANG LIU, DEPT. OF ELECTRICAL AND INFORMATION TECHNOLOGY



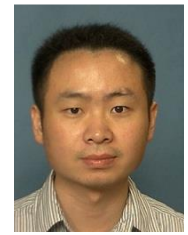
The team – Digital Asic Group


Prof. Peter Nilsson


Prof. Viktor Öwall


Assoc. Prof. Erik Larsson


Assoc. Prof. Joachim Rodrigues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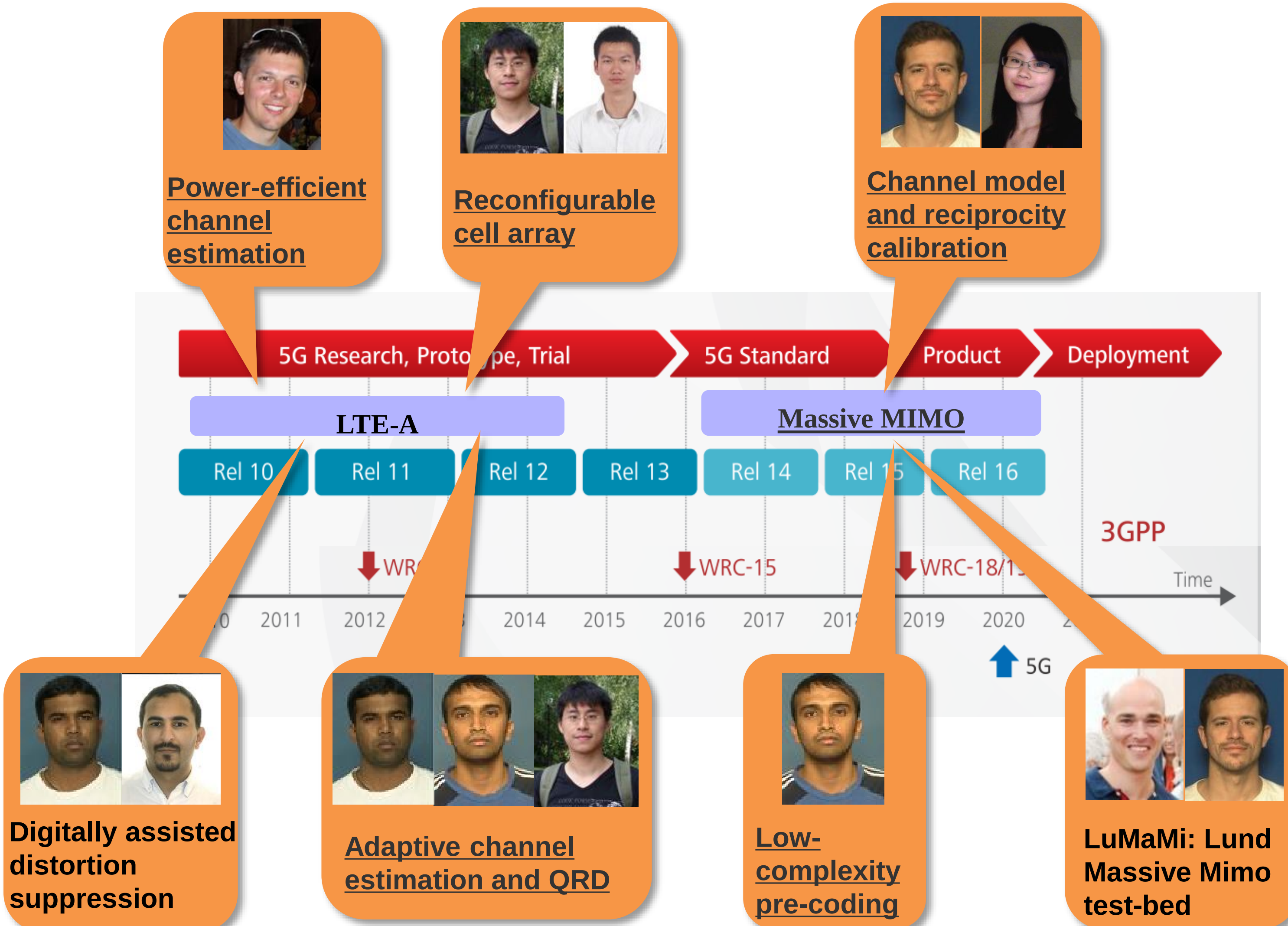
The research



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Energy-efficiency computing

How do we compute?

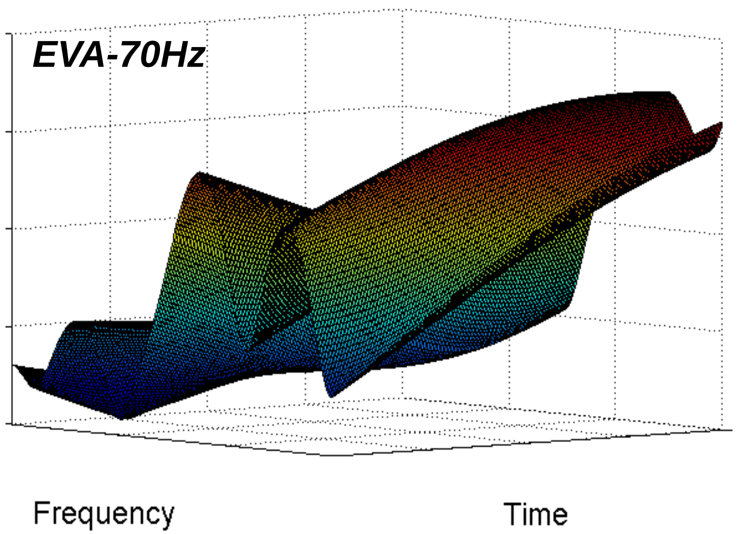
2134 x 15 = 32010

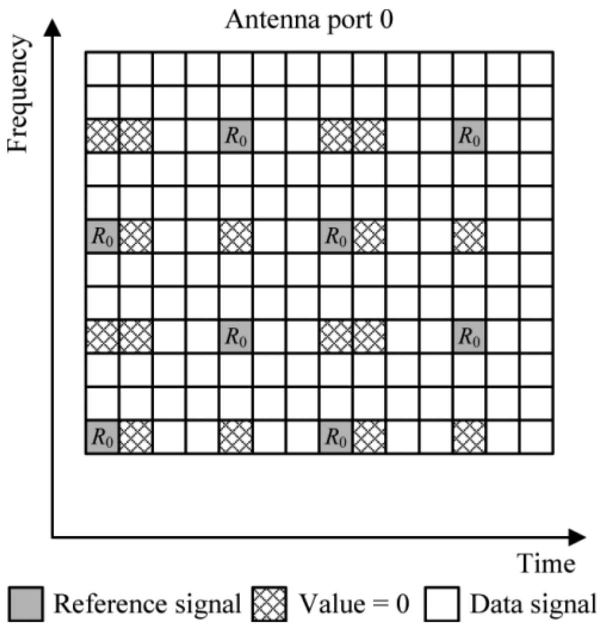
2136 x 15 = ? 32010+(2136-2134)x15 = 32040

Observations?

1. Calculations are complicated…
2. Correlations can make the job easier

Correlations in wireless communication





Channel estimation → **Channel matrix process (QRD, inv.)** → **Data detection**

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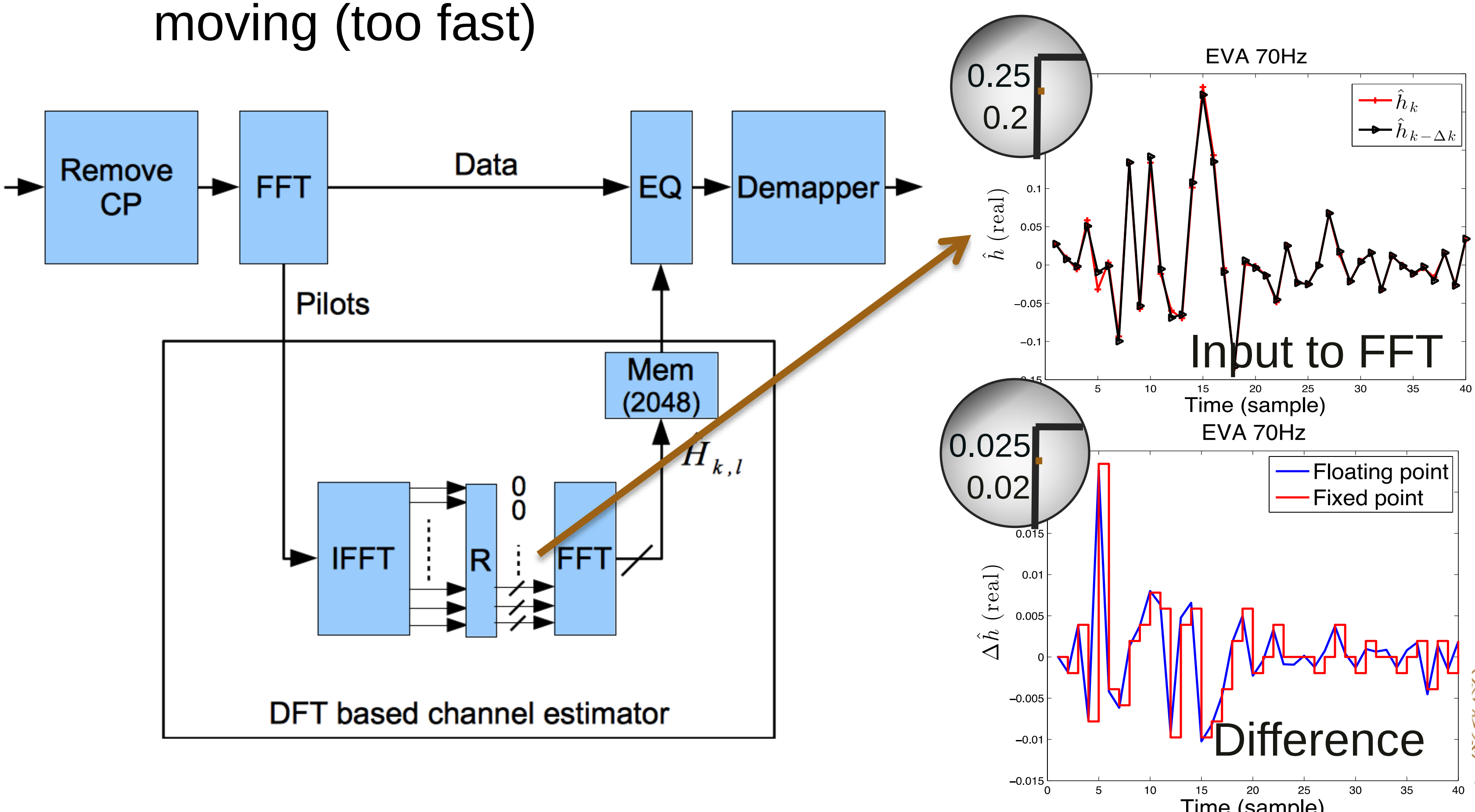
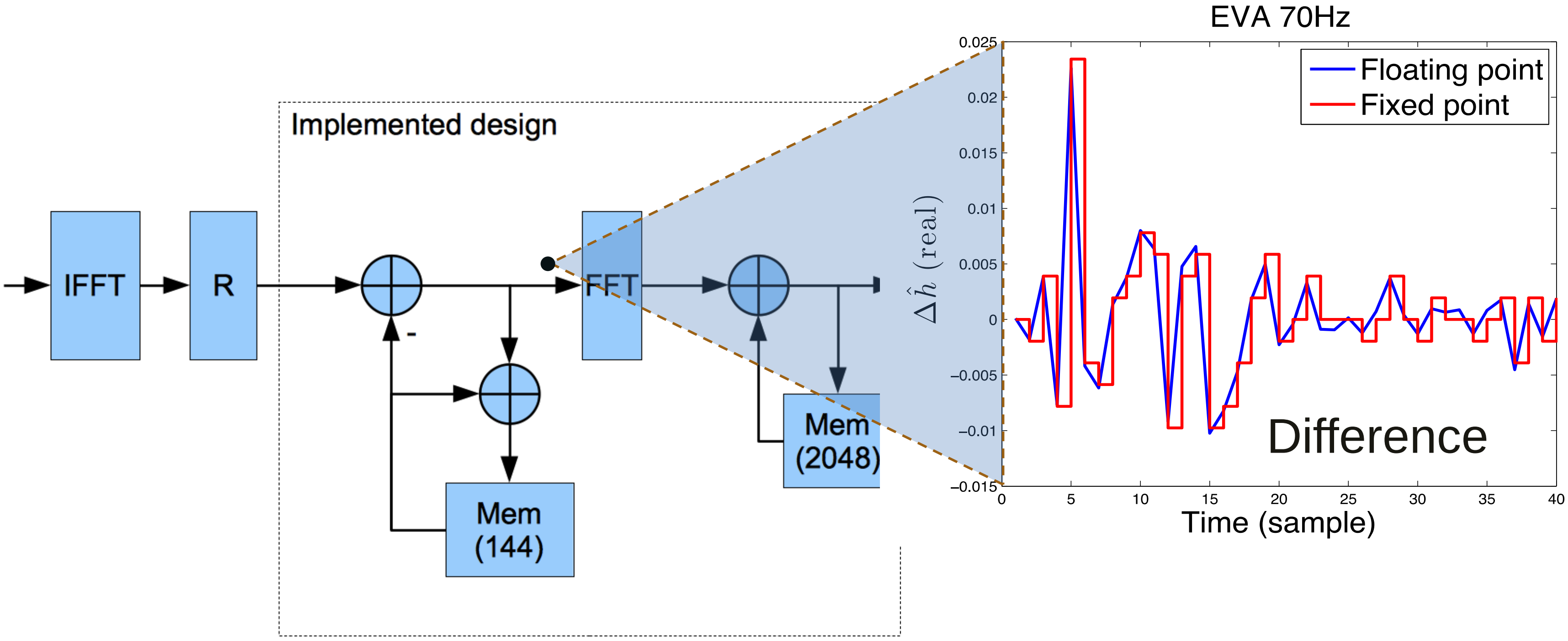
Low-complexity channel estimation: explore time-domain correlations

- Channel do not change so much when the terminal is not moving (too fast)

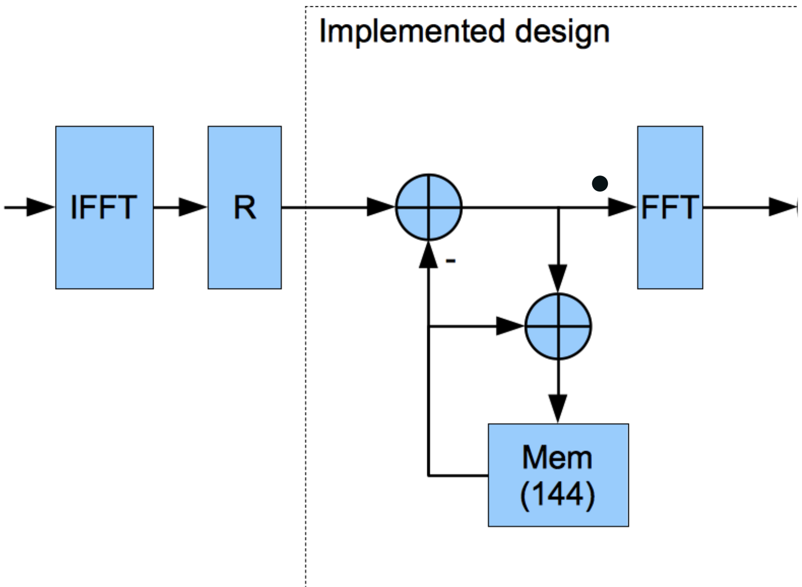


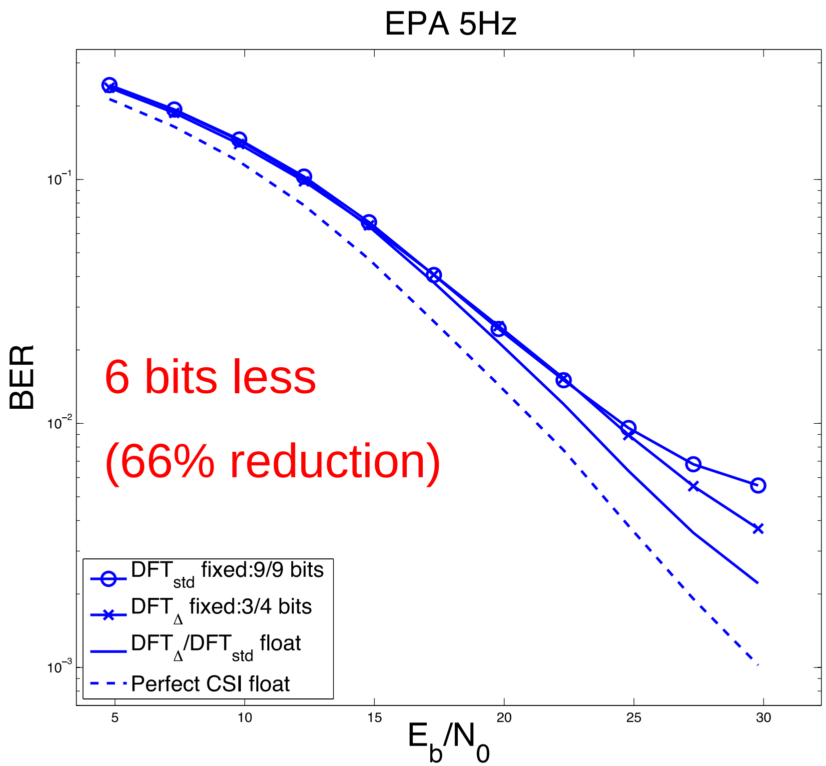
Low-complexity channel estimation



- Fewer bits are used in the FFT compared to the original DFT based channel estimator

Low-complexity channel estimation





- Fewer bits are used in the FFT compared to the original DFT based channel estimator

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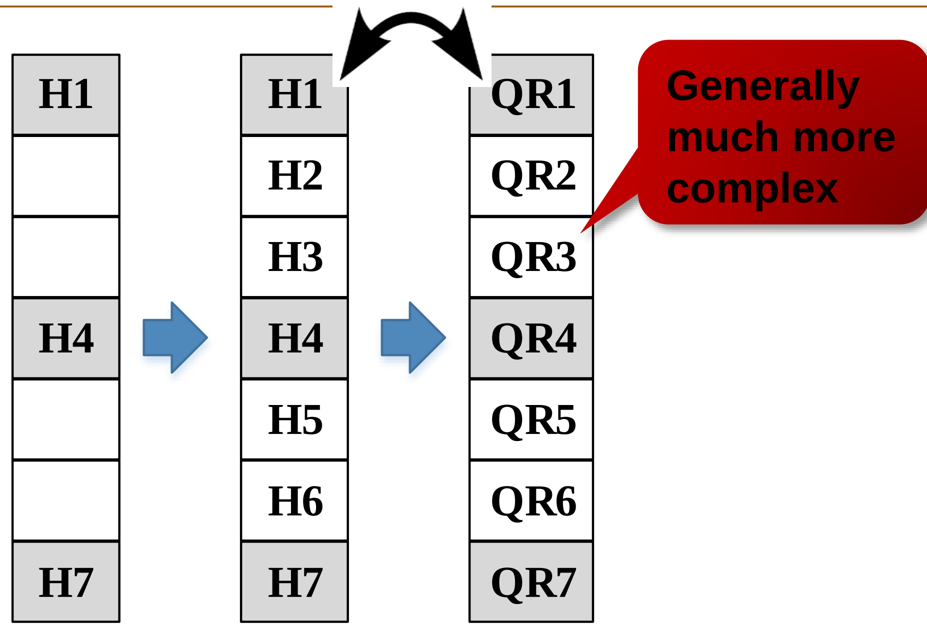
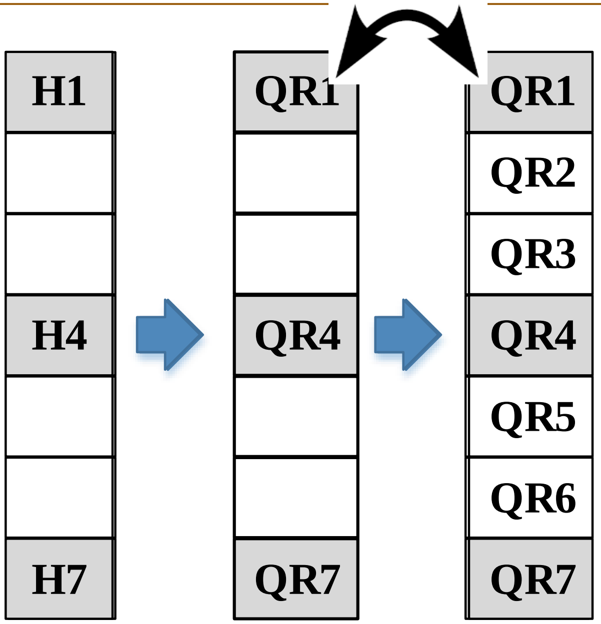
Low-complexity QRD: explore frequency-domain correlations



- Aiming for very low-complexity **linear QR interpolation**
- Adaptively adjust **interpolation distance**
  - depending on channel, noise, and QoS requirement

Low-complexity QRD: explore frequency-domain correlations



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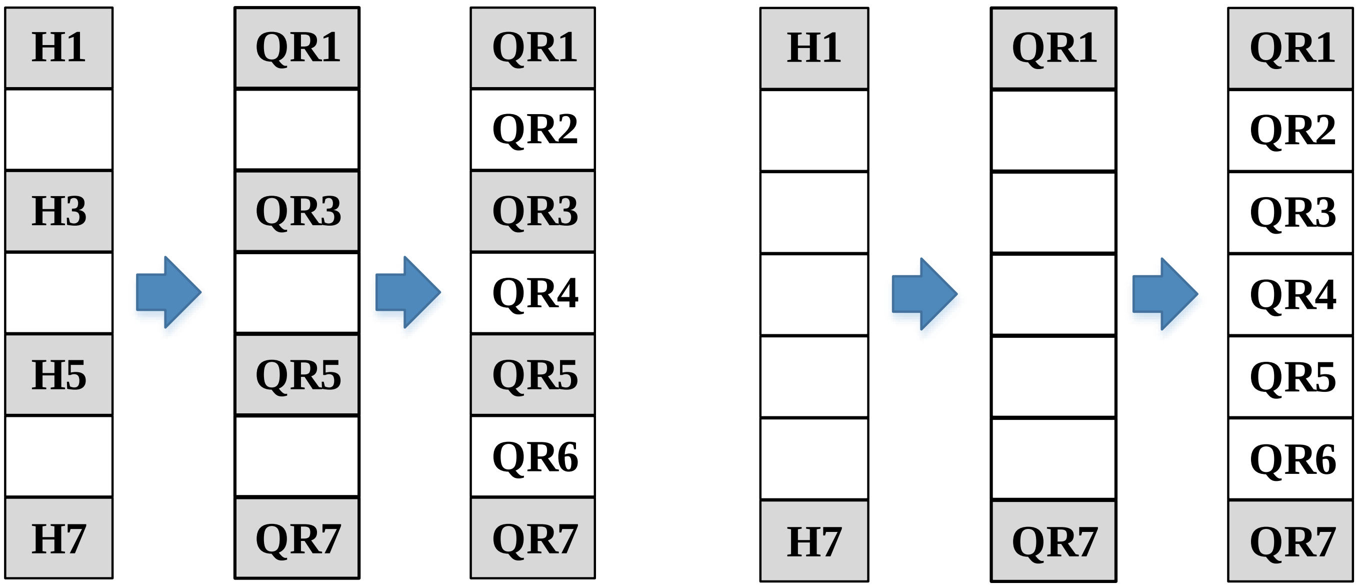
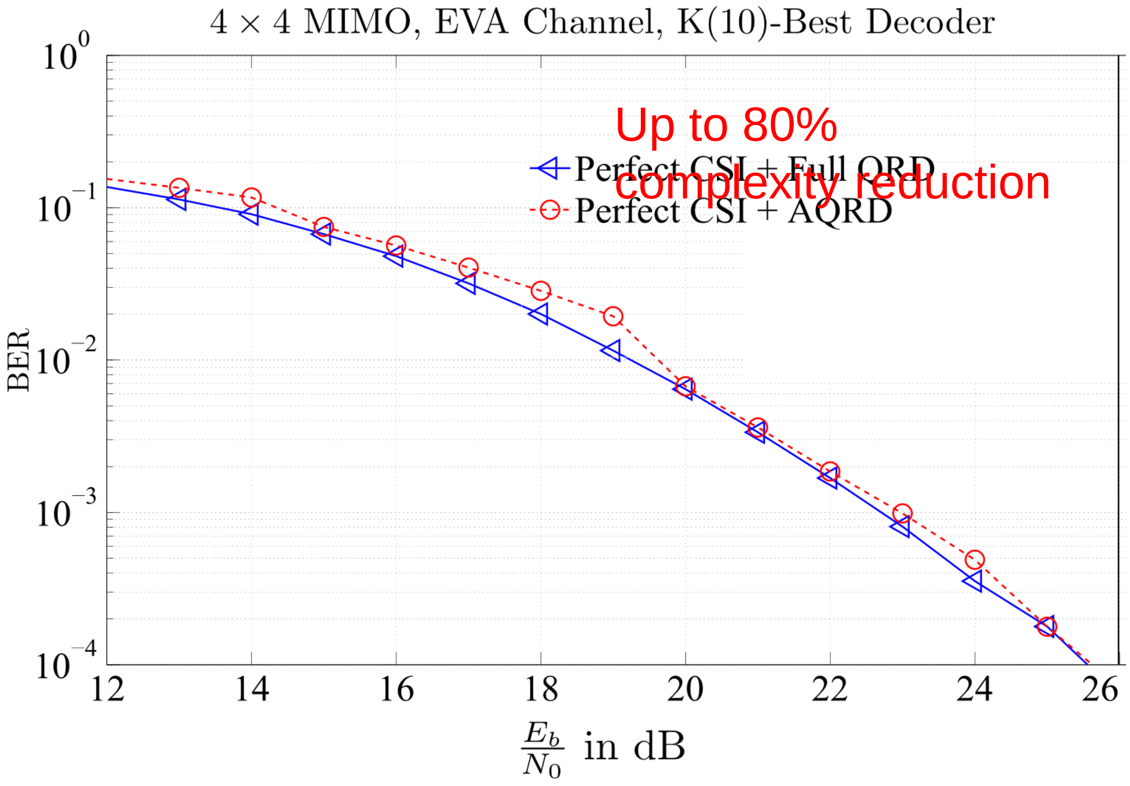
Low-complexity QRD: explore frequency-domain correlations



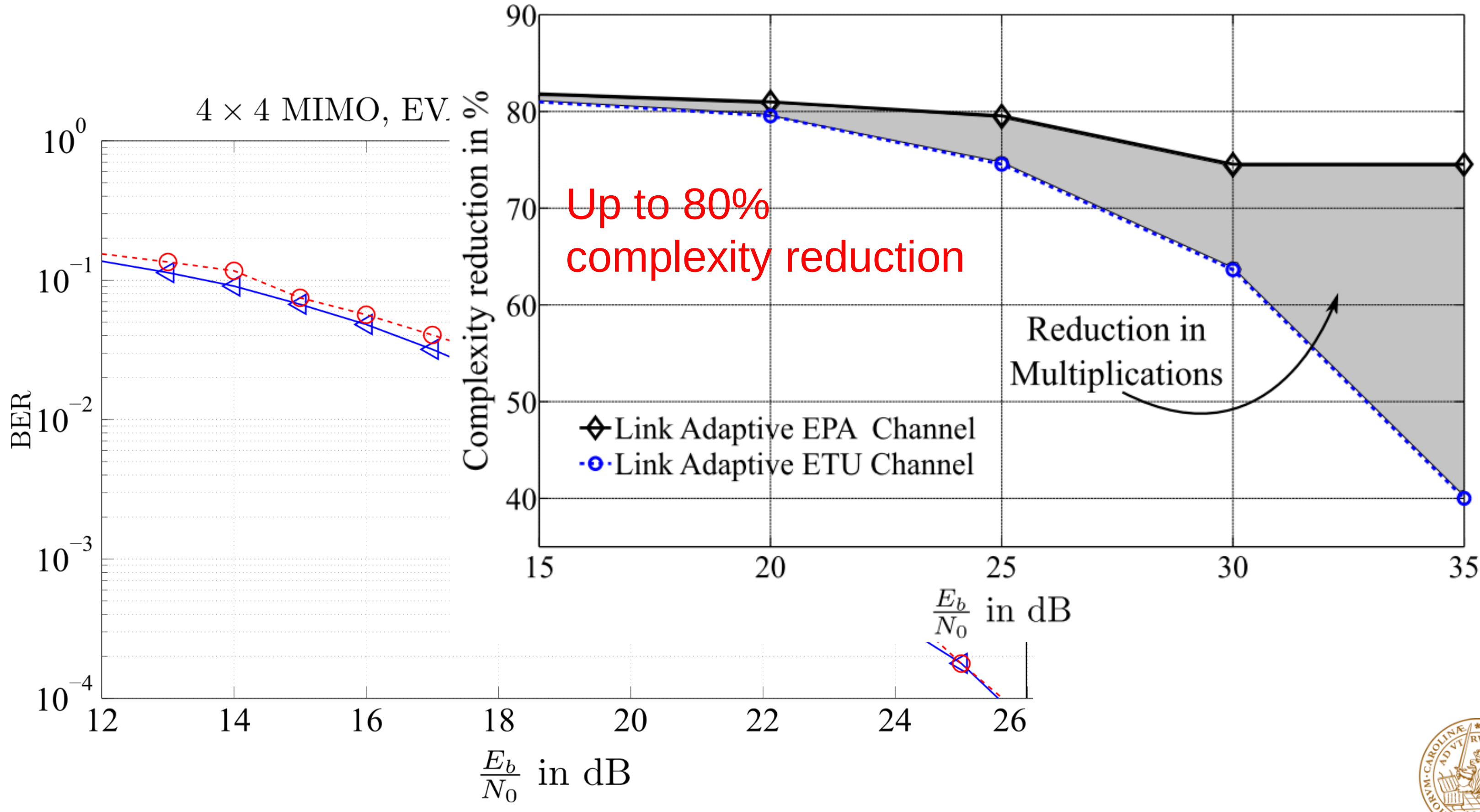
Low Correlation High Correlation

- Aiming for very low-complexity **linear QR interpolation**
- Adaptively adjust **interpolation distance**
  - depending on channel, noise, and QoS requirement

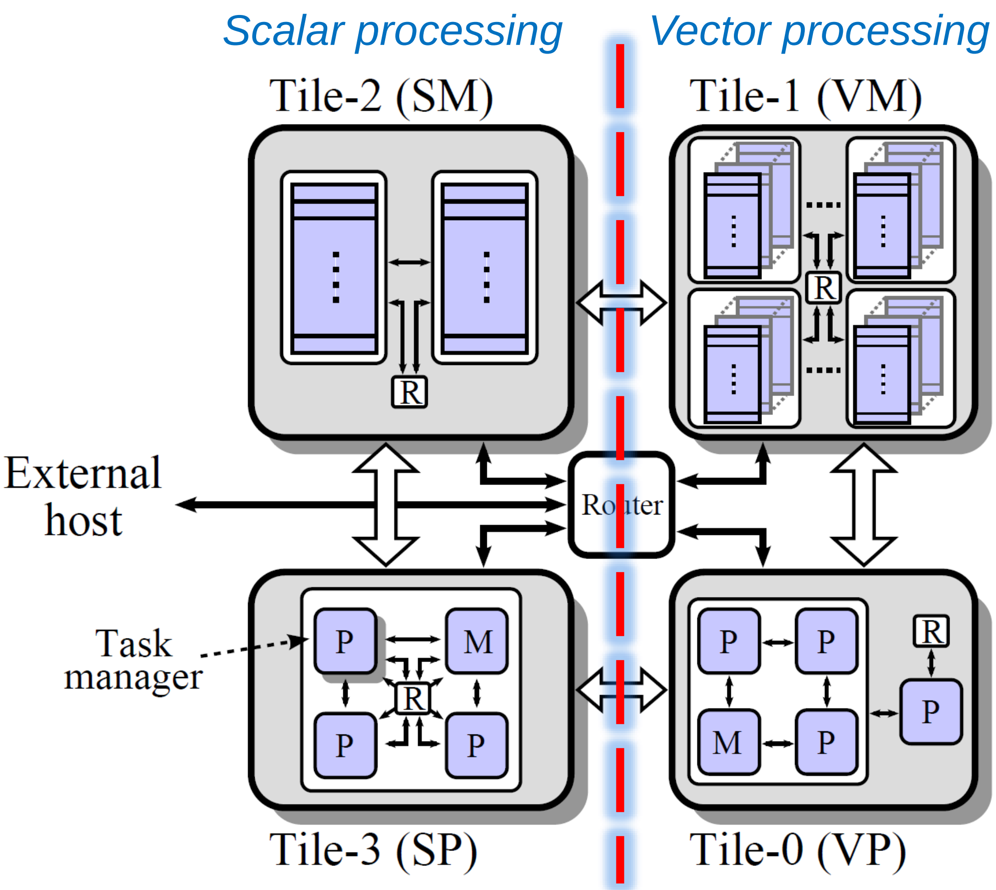
Low-complexity QRD



Low-complexity QRD

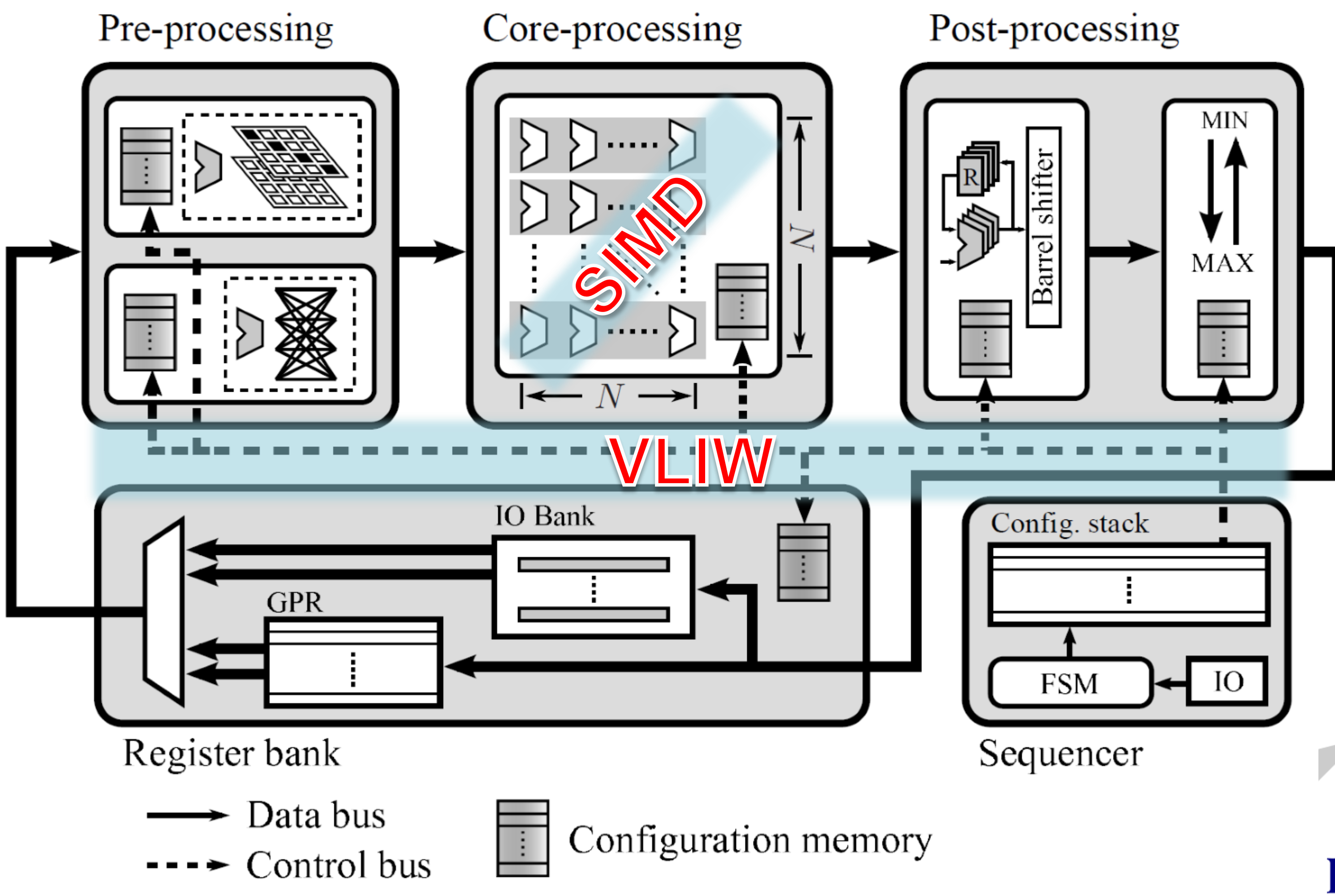


Reconfigurable cell array



- Tile-0: vector processors
- Tile-1: vector memory
- Tile-2: scalar memory
- Tile-3: scalar processors

Vector processing cell

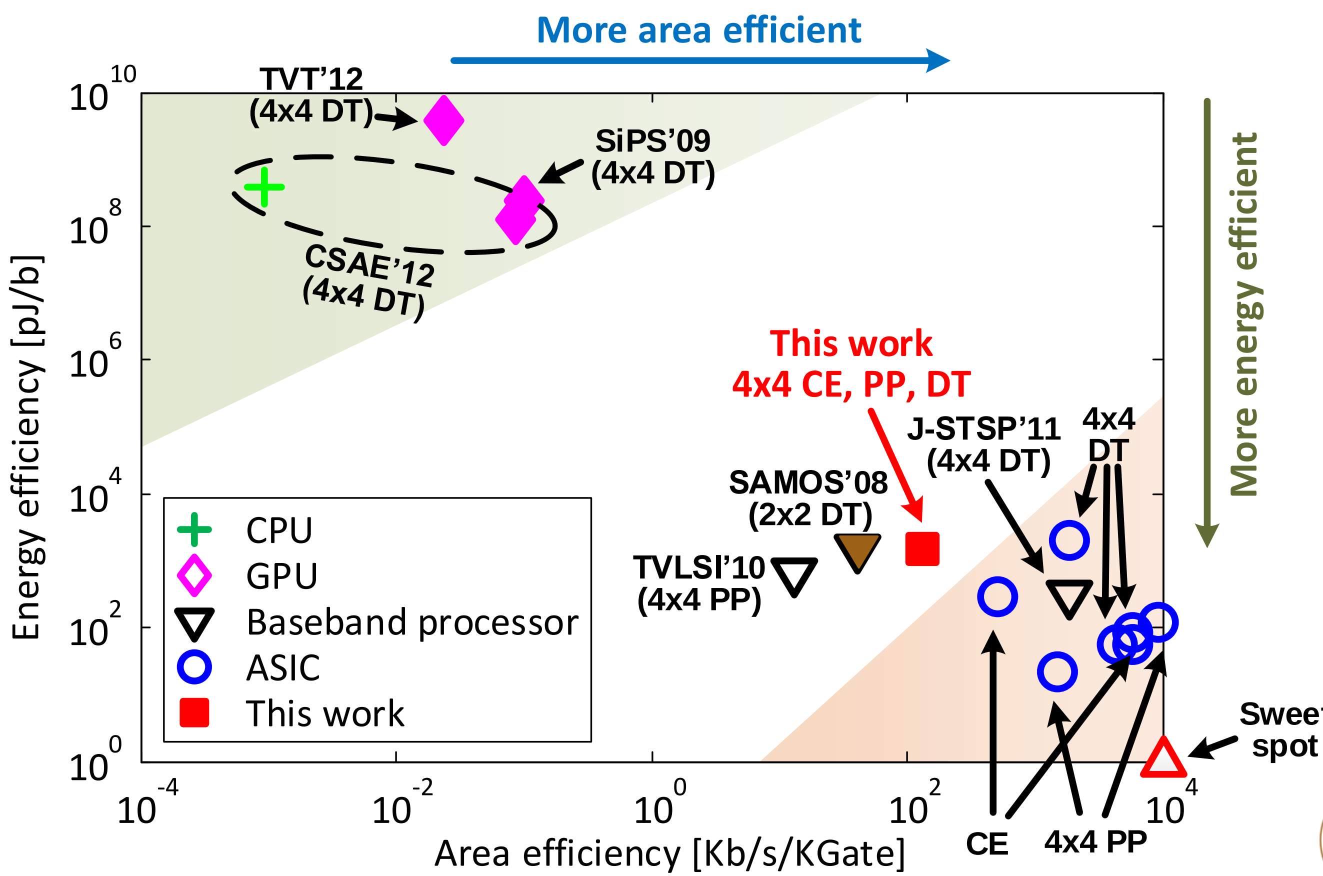


Area & energy efficiency

Layout with 65nm CMOS

- **Core area: 8.88mm^2**
- **Throughput: 368Mb/s**
- **Power: 550mW@1.2V and 500MHz**
- **CE, QRD, Detection**

Area & energy efficiency

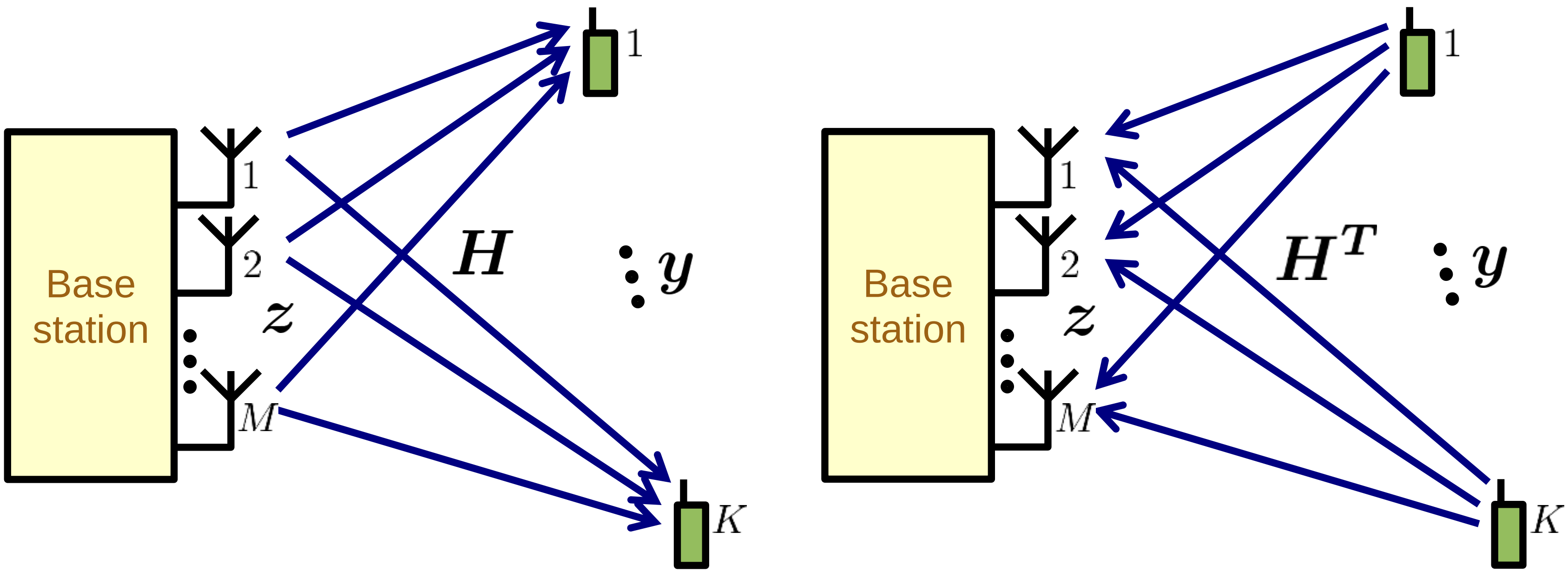


With data memory included.

CE (channel estimation), PP (matrix pre-processing), DT (detection)

Massive (multi-user) MIMO
TDD operation

Massive MIMO implies that we let the number of base station antennas (*M*) grow very large … in the hundreds!



Down-link:

$$y = Hz + n$$

Up-link:

$$z = H^T y + v$$

Channel reciprocity assumed

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We experience ”new” channel propeties

- Physically large arrays with many antenna elements
  - have large Rayleigh distances, enabling the focus of energy not only in direction but also in ”depth”
  - may experience power variations/large scale fading across the array
  - make channels to different users become orthogonal as the number of antenna elements grows (under favourable propagation)
  - even with simple precoding, channel variations average out

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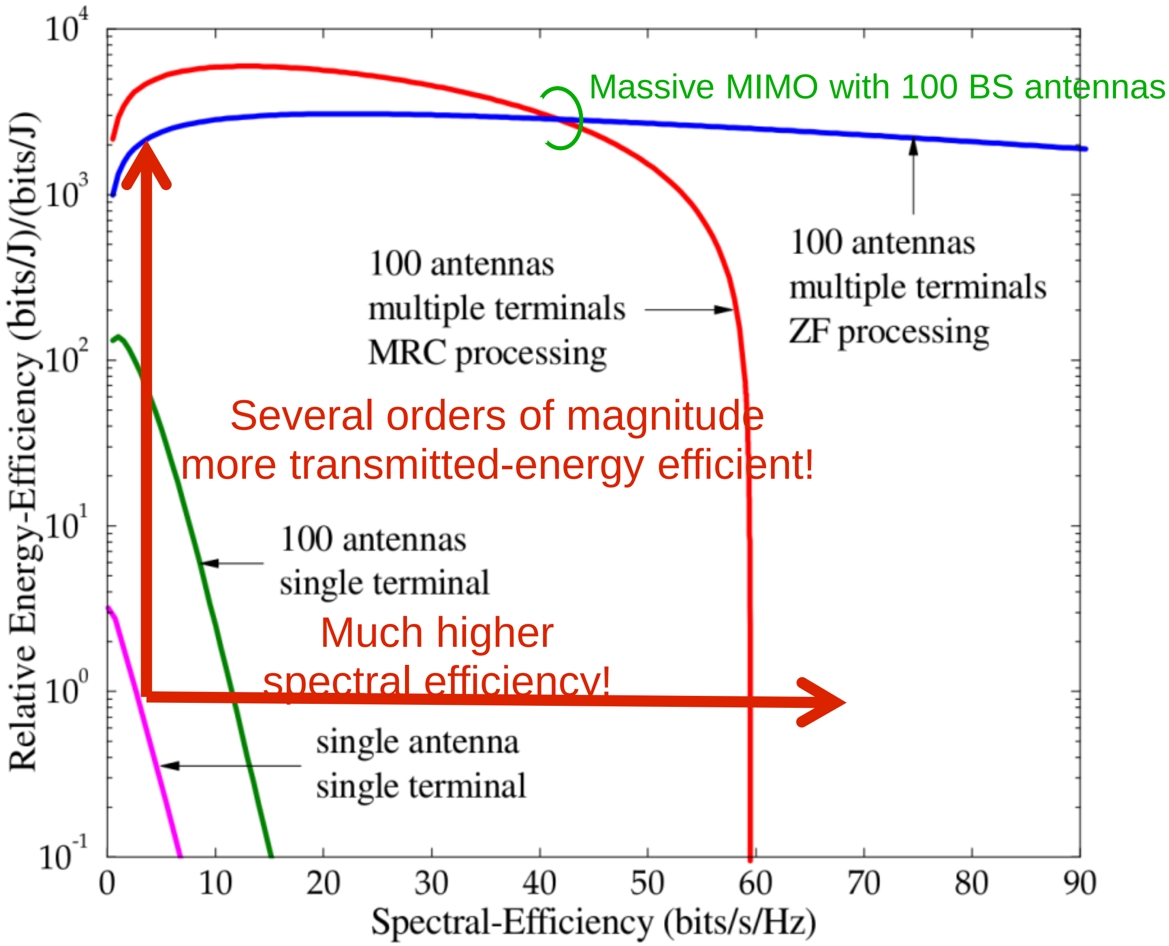
Why do we care about massive MIMO?



[Plot from Larsson, E. ; Edfors, O. ; Tufvesson, F. ; Marzetta, T., “Massive MIMO for next generation wireless systems”, IEEE Communications Magazine, Vol. 52 , Issue 2, 2014]

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Practical challenges and research topics

- “Channel” reciprocity and its calibration
- Fast and power-efficient baseband processing
  - Pre-coder
  - Detector
- Low-cost front-end and front-end impairments
  - PAPR
  - Phase noise
  - Quantization
- Highly-parallel and reconfigurable computing
- …

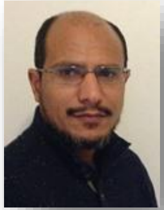
Project members at Lund

Wireless Communication ⟷ Circuit design

Fredrik Rusek
Assoc. Professor
Comm. theory and algorithm design

Ove Edfors
Professor
System and algorithm design

Fredrik Tufvesson
Professor
System design and propagation



Ghassan Dahman
Asstn. Professor
Antenna systems and propagation

Viktor Öwall
Professor
Digital circuit design

Liang Liu
Asstn. Professor
Baseband processing and circuit design

Xiang Gao
PhD stud.
Precoding, PHY layer and propagation

Dimitrios Vlastaras
PhD stud.
Software design and channels models

Joao Vieira
PhD stud.
Propagation and radio systems

Hemanth Prabhu
PhD stud.
Precoding and distrib. processing

Steffen Malkowsky
PhD stud.
Digital circuits and processing

Opening
Post-Doc
Reconfigurable architecture

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MAMMOET consortium

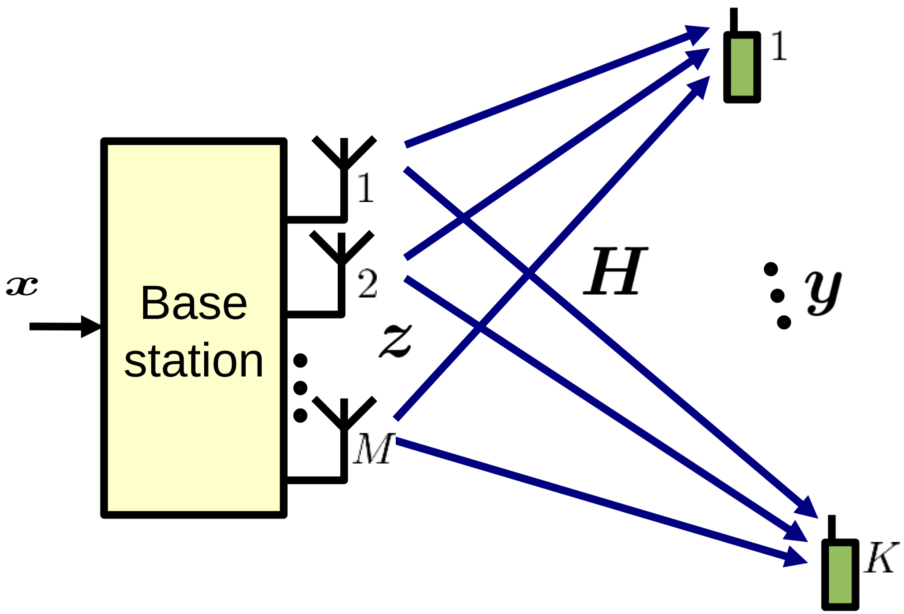
Consortium:

The MAMMOET consortium is well-positioned to achieve its objectives by bringing together a European team of leading industrial and research companies, a research oriented SME as well as highly respected universities. These 8 project partners from 4 different countries form a complete chain stretching from basic research and service design, via applied research, up to end-user oriented service providers.

Project Partners:

1. Technikon Forschungs- und Planungsgesellschaft mbH (Austria)
2. Interuniversitair Micro-Electronica Centrum VZW (Belgium)
3. Ericsson AB (Sweden)
4. Infineon Technologies Austria AG (Austria)
5. Katholieke Universiteit Leuven (Belgium)
6. Lunds Universitet (Sweden)
7. Linköpings Universitet (Sweden)
8. Telefónica Investigación y Desarrollo SA (Spain)

Linear pre-coding



Element *k* of *x* intended for the *k*th terminal:

$$\boldsymbol{z} = \boldsymbol{W}\boldsymbol{x}$$

Terminals receive one element each of

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{W}\boldsymbol{x} + \boldsymbol{n}$$

Maximum-ratio transmission (MRT)

$$\boldsymbol{z} = \boldsymbol{H}^{H}\boldsymbol{x}$$

Hermitian transpose of channel

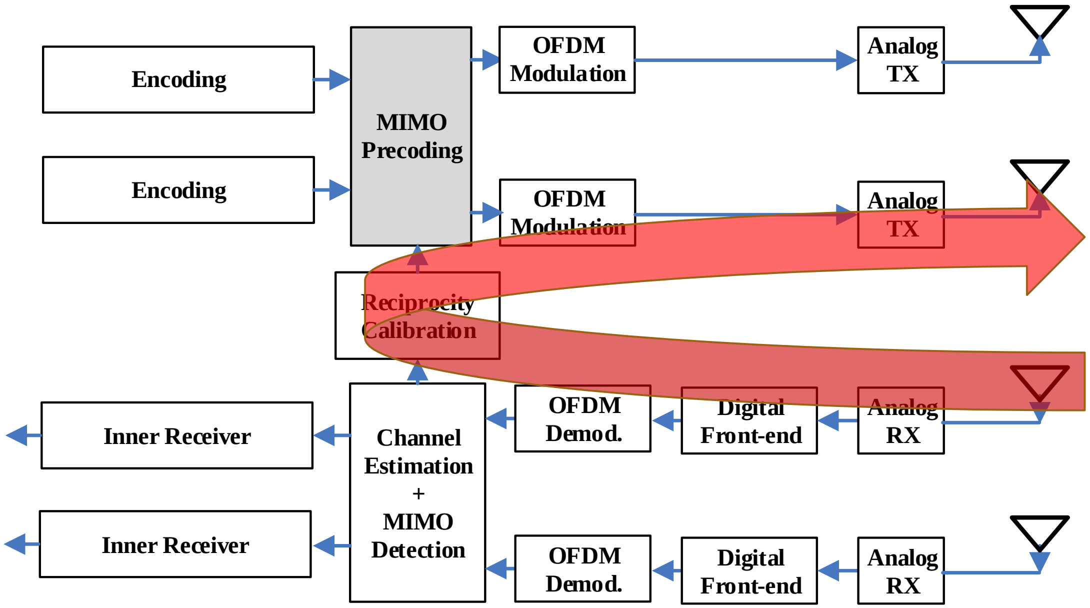
Zero-forcing (ZF)

$$\boldsymbol{z} = \boldsymbol{H}^{+}\boldsymbol{x}$$

Pseudo-inverse of channel

”Low-complexity” linear pre-coding

- Linear pre-coding is not low-complexity anymore…
  - $H_{ZF} \sim H^H (HH^H)^{-1}$
  - $O(10^4)$ for a 100 base station antennas and 10 users
- Processing latency becomes critical issue

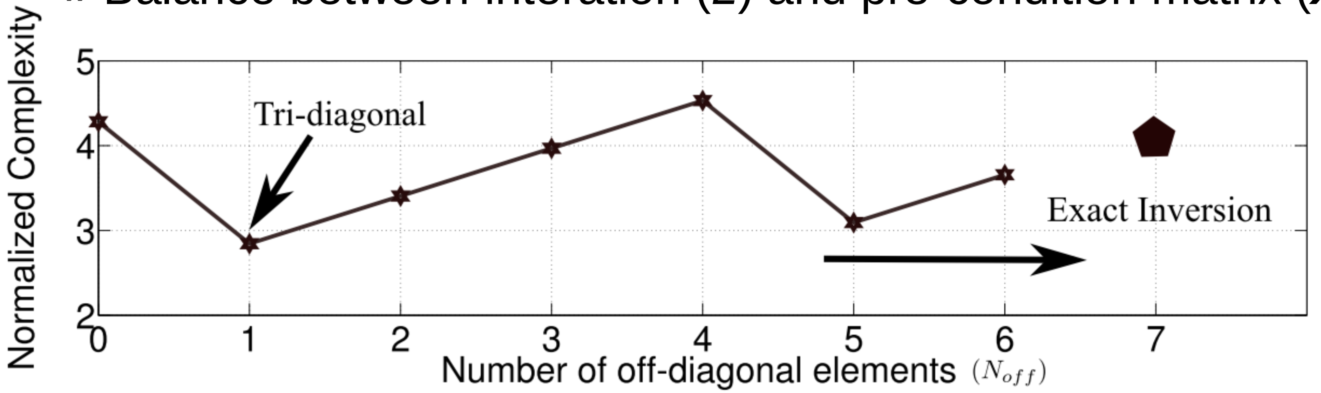


Low-compleixty linear pre-coding

- Neumann series based ZF pre-coding
  - HH^H is diagonally dominante
  - NS-approximation:

$$\boldsymbol{Z}^{-1} \approx \sum_{n=0}^{L} \left(\boldsymbol{I}_K - \boldsymbol{X}^{-1}\boldsymbol{Z}\right)^n \boldsymbol{X}^{-1}$$

  - Complexity optimizaiton
    - » Balance between interation (*L*) and pre-condition matrix (***X***)



(b) Complexity to achive 16-bit accuracy with different pre-condition matrices.

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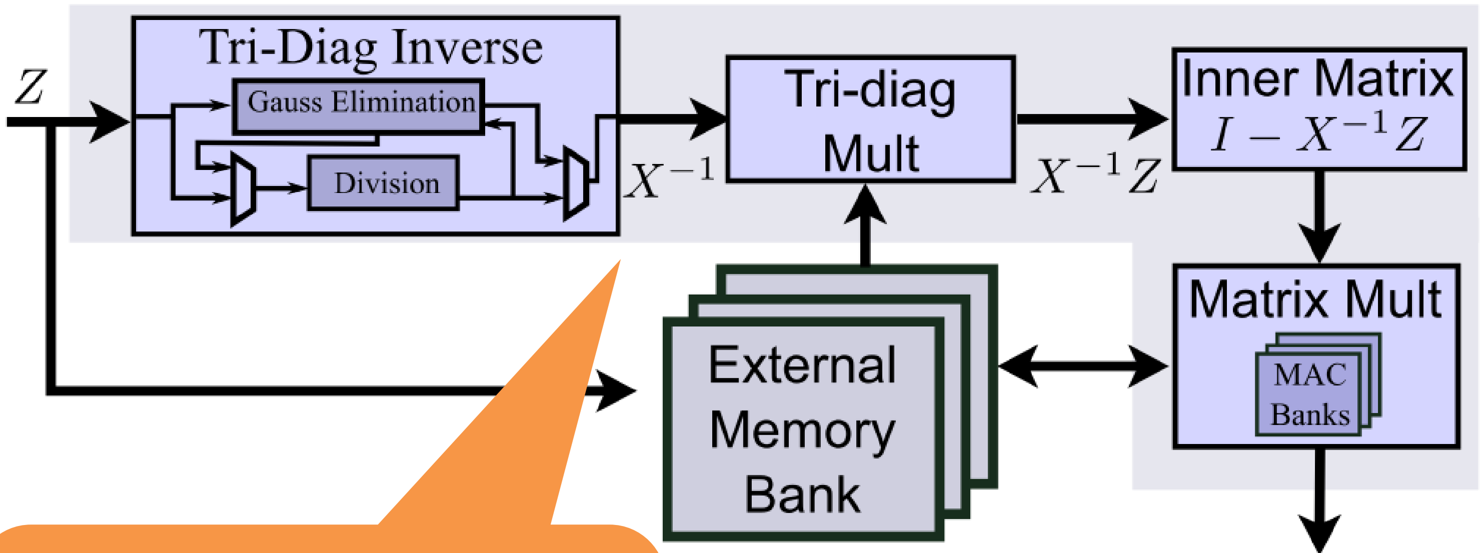
Low-compleixty linear pre-coding



- **Synthesis using 65nm CMOS**
- **Support 2-16 users**
- **0.5M Inversions/sec**
- **265 cycle latency~2.65 μs @ 100MHz clock**

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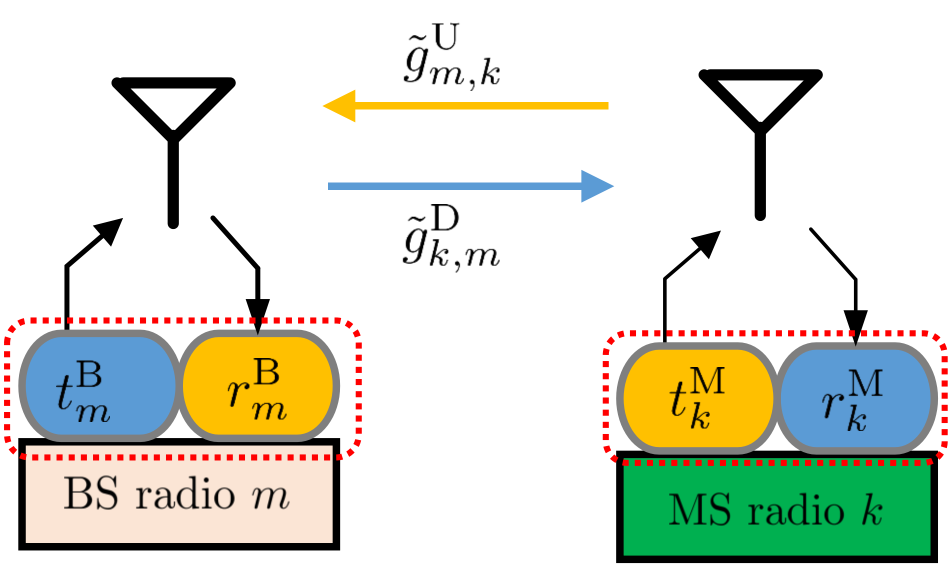
Reciprocity calibration

- Channel reciprocity is the main assumption to realize efficient TDD Massive MIMO
  - downlink beamforming is performed based on uplink pilots
  - ”channel” consists of propagation and tranceiver response

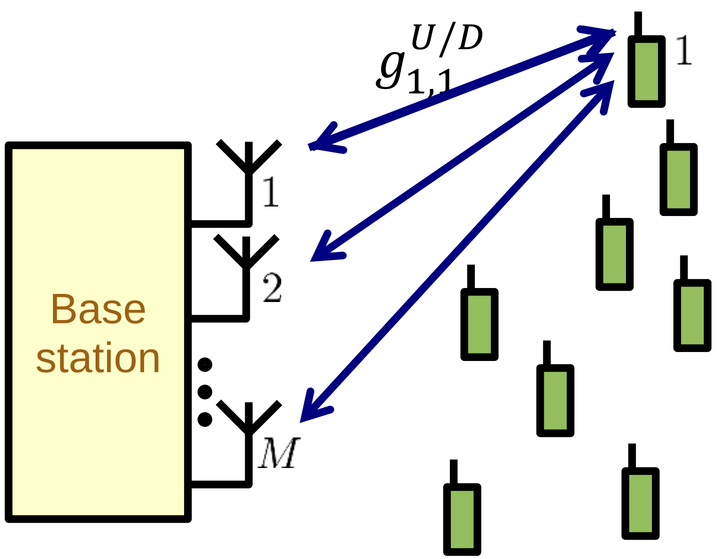


$$g^{\mathrm{U}}_{m,k} = r^{\mathrm{B}}_m \, \tilde{g}^{\mathrm{U}}_{m,k} \, t^{\mathrm{M}}_k$$
$$g^{\mathrm{D}}_{k,m} = r^{\mathrm{M}}_k \, \tilde{g}^{\mathrm{D}}_{k,m} \, t^{\mathrm{B}}_m,$$

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

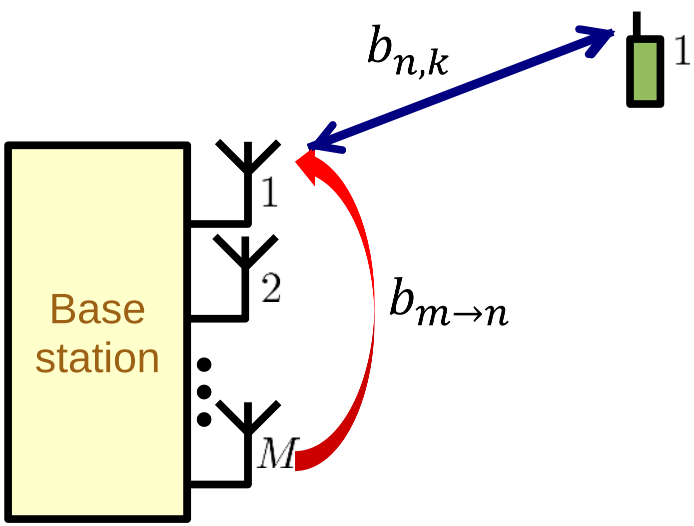
Reciprocity calibration

- Calibrate by feeding back?



Reciprocity calibration

- Calibrate by feeding back?
- Calibrate by referering to the same base-station antenna
  - What is the acceptable calibration quality in practice?
  - How often should we do it?



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

Long coherence time

down-link pilot

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Conclusions

- Digitally assisted radio design
- Adaptive computing for energy-efficient processing
- Reconfigurable circuits for flexibility
- Algorithm-architecture co-design for implementation efficiency
- MIMO goes to Massive
- From theory to practice

Posters