Massive MIMO
Overall system complexity

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on behalf of the MAMMOET consortium

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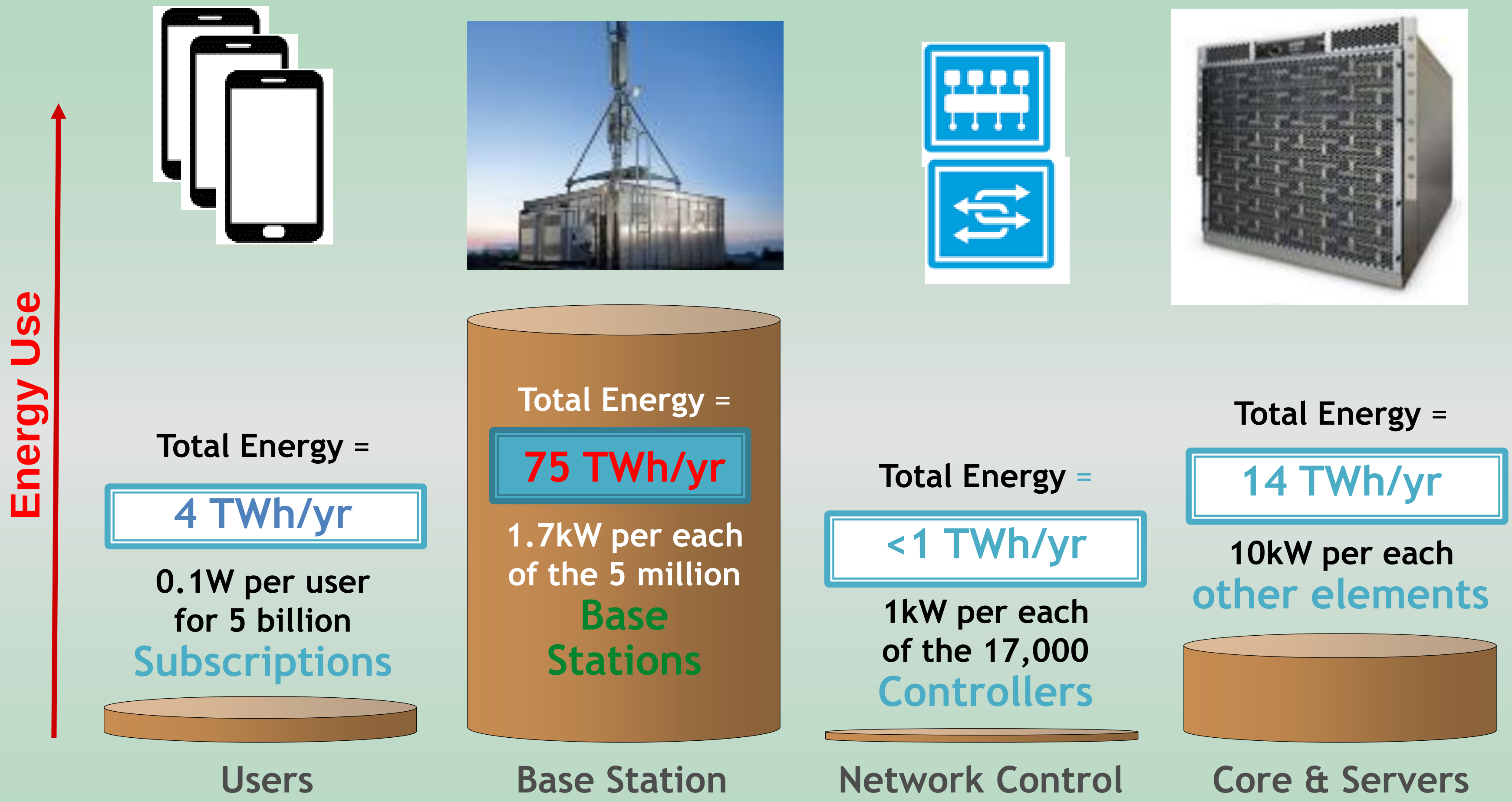
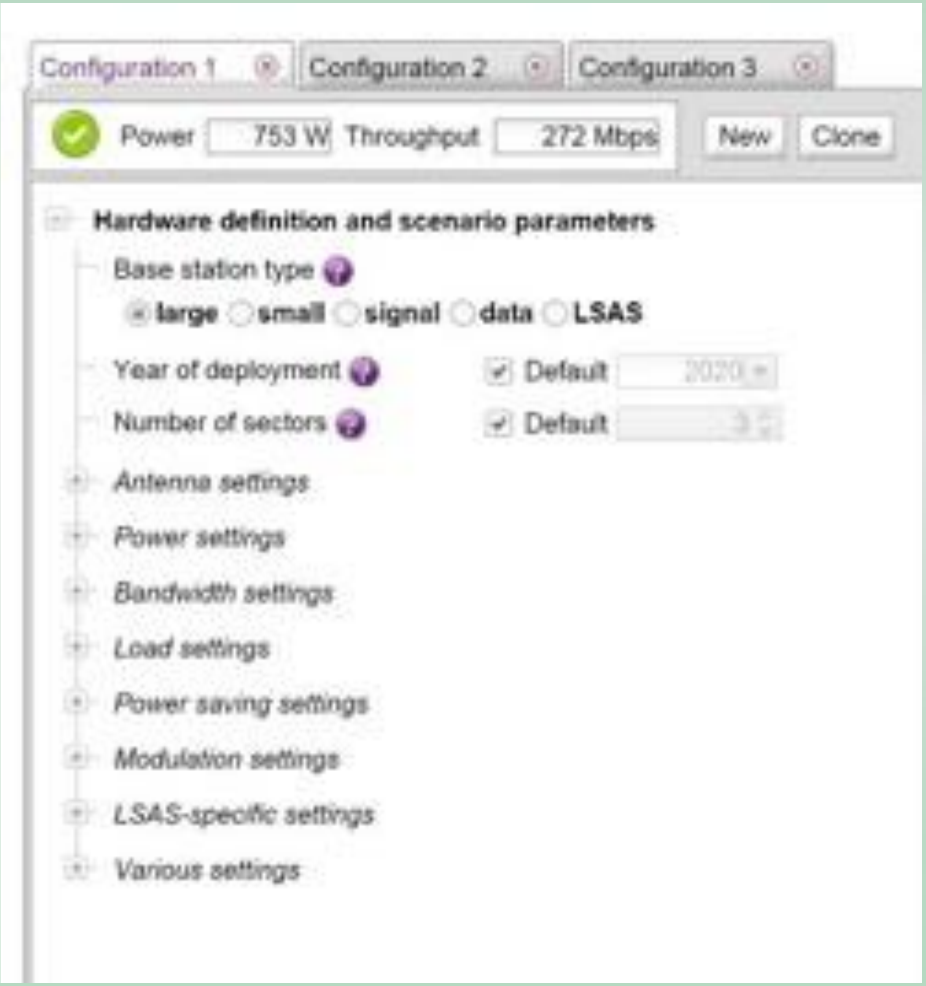
Massive MIMO boosts energy efficiency: cooperating benefits

- Array gain => total radiated power ~ 1/M
- Diversity gain additionally
- Channel hardening: reduce (remove) fading margins
- Averaging properties allowing much simpler (low-power) hardware
- Opening new application-architecture-circuit options:
  - Low output power/antenna enable digital Transmitters
  - Approximate computing may suffice
  - …



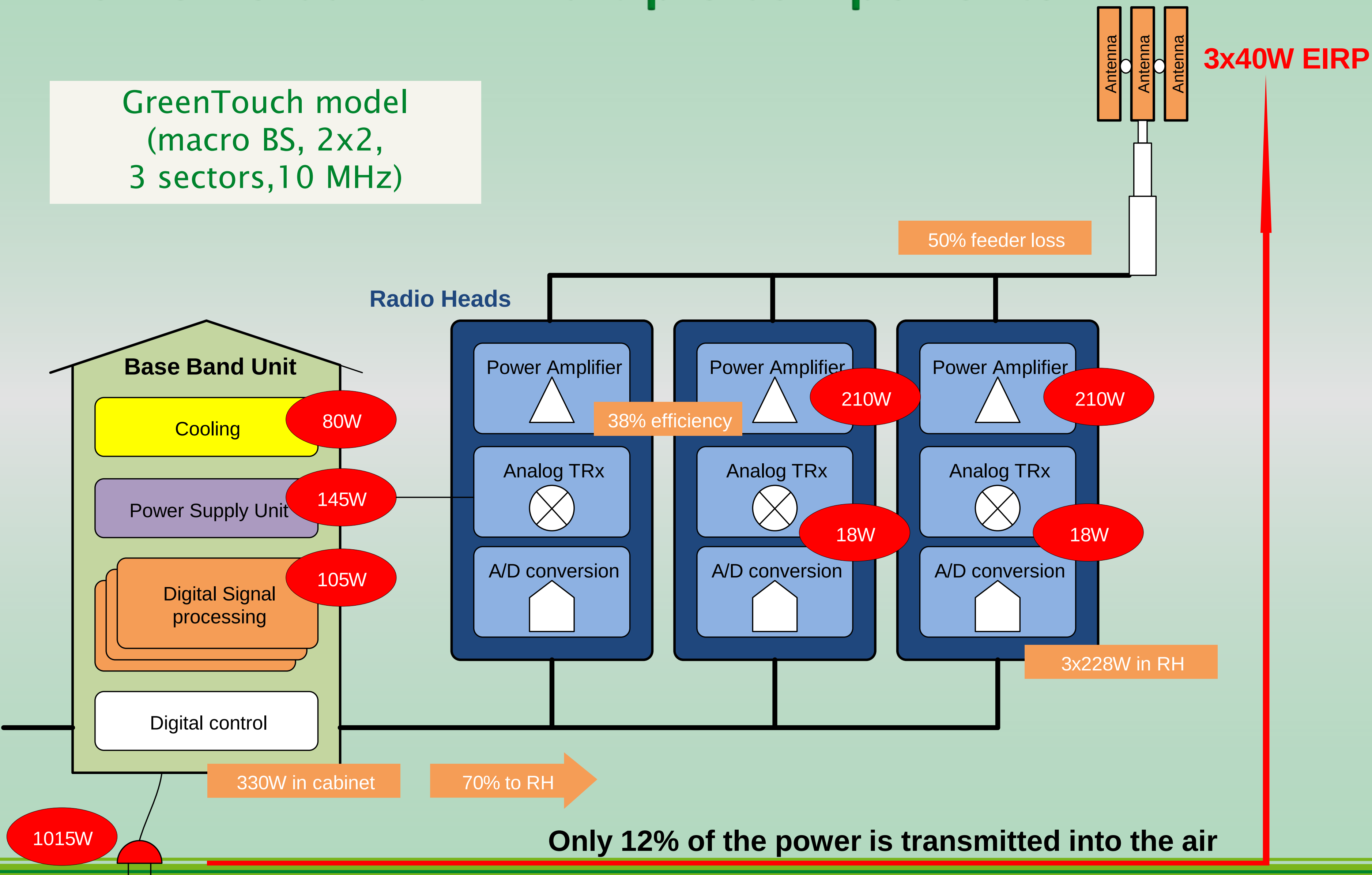
With 80%, the base stations are by far the main consumers

The total power picture: models at help



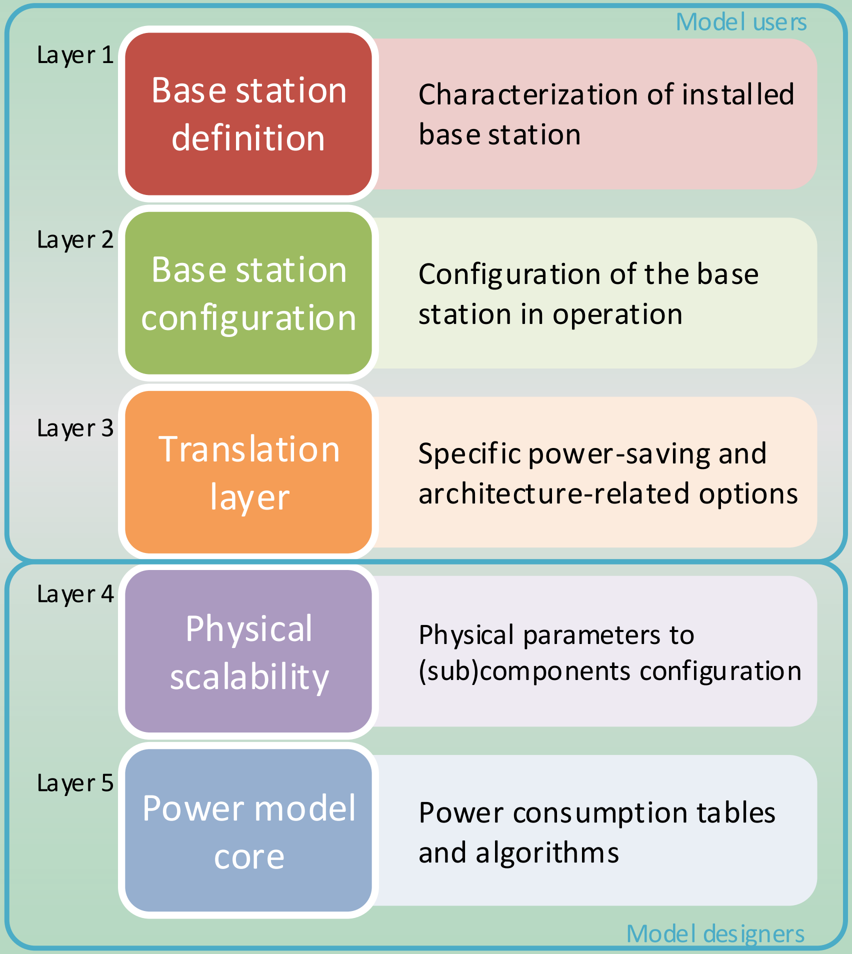
Power is burnt in multiple components

GreenTouch model
(macro BS, 2x2,
3 sectors,10 MHz)



Only 12% of the power is transmitted into the air

Massive MIMO vs. other cellular BS



Different base station types:

- *Large*: macro, 10 - 100 W output, high accuracy architecture, multi-sector, cooled
- *Small*: pico, 0.1 - 1 W output, relaxed specifications, single-sector
- *Massive MIMO*: completely different architecture, 10 - 100 mW per antenna, coverage of *large* BS, hardware of *small* BS

Five main components:

- PA
- Analog FE
- Digital BB
- Digital control
- Power supply

Modeling the power consumption of Massive MIMO: low-accuracy assumptions

- Output power reduced from Massive MIMO link budget
- Large number of antennas => overhead power not negligible
- PA close to saturation
- Low signal accuracy of analog components
- Low resolution of digital components
  - Simpler arithmetic operations
  - Smaller memories

Why does it still work?

- Useful signal adds coherently over antennas
  - Interference and impairments add non-coherently
  - This improves experienced SNIR with respect to single-antenna values
- Overall power level is reduced, even more per antenna
  - This makes respecting out-of-band specs much easier

Scaling output power for Massive MIMO

- Objective: keep a similar coverage and user (SINR)
  - Ref. macro: 4 antennas, P_{ref} = 43 dBm/ant. (49 dBm total), 3 sectors
  - Massive MIMO: M = 200 antennas, K = 30 users, 1 sector
- Scaling approach
  - Start from SISO link budget, assuming infinite diversity (from coding over subcarriers) => P_{ref} total output power required
  - Scale to an M x 1 system, assuming perfect CSI and precoding => P_{ref} / M total (or P_{ref} / M^2 per antenna)
  - Serving K users => total power multiplied by K such that each user keeps the same power => $K\, P_{ref} / M$
  - Additional term R_{Power} represents effect of potential reduced spectral efficiency in Massive MIMO (overhead)

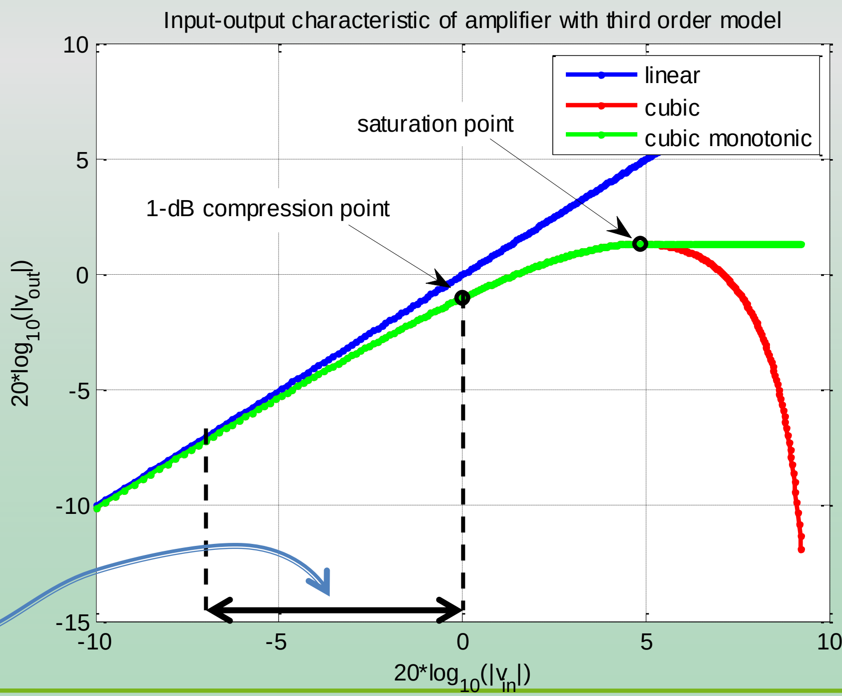
PA model: adapted for Massive MIMO

- Proposed scenario
  - 35 dBm total output power – 12 dBm per-antenna
- Traditional PA trade-off
  - High linearity or high efficiency of very complex architectures
- Massive MIMO PA proposal
  - No need for high accuracy thanks to Massive MIMO robustness
  - Relaxed out-of-band specs thanks to reduced power levels
  - 50% efficiency realistic in strong non-linear operation
  - Minimal consumption value added (not arbitrary low PA power)

PA non-linearity:
creates non recoverable distortion

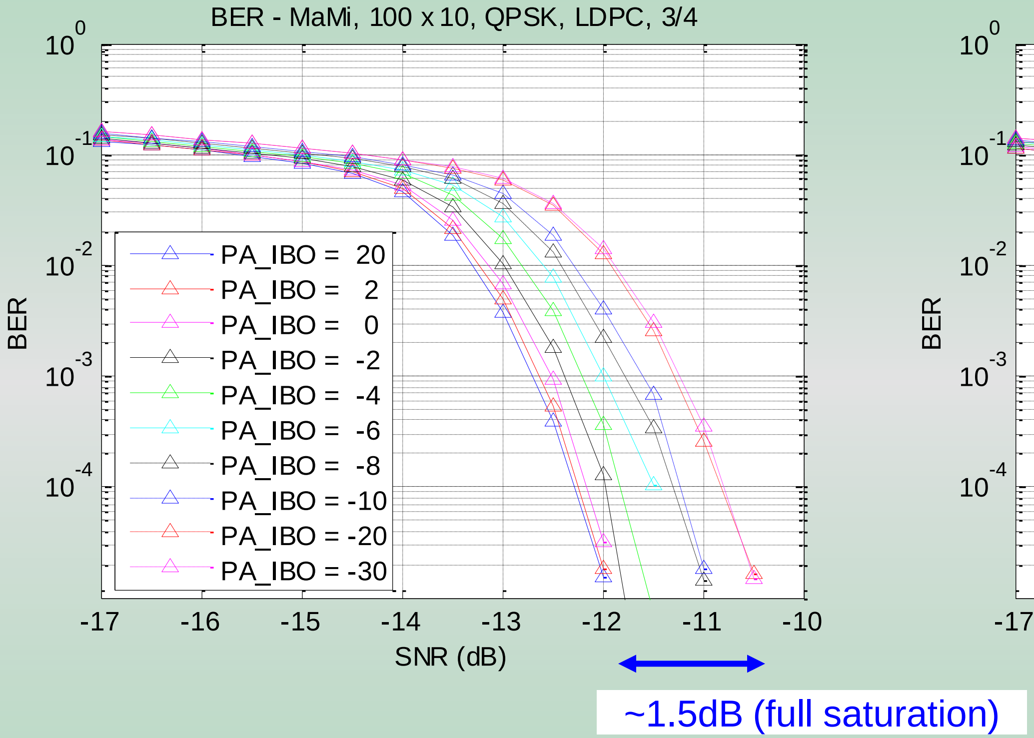
- Simulated with cubic monotonic model
- Output power renormalized (constant output constraint)
- PA characterization by 1 dB compression or saturation points
- Back-off [dB] range

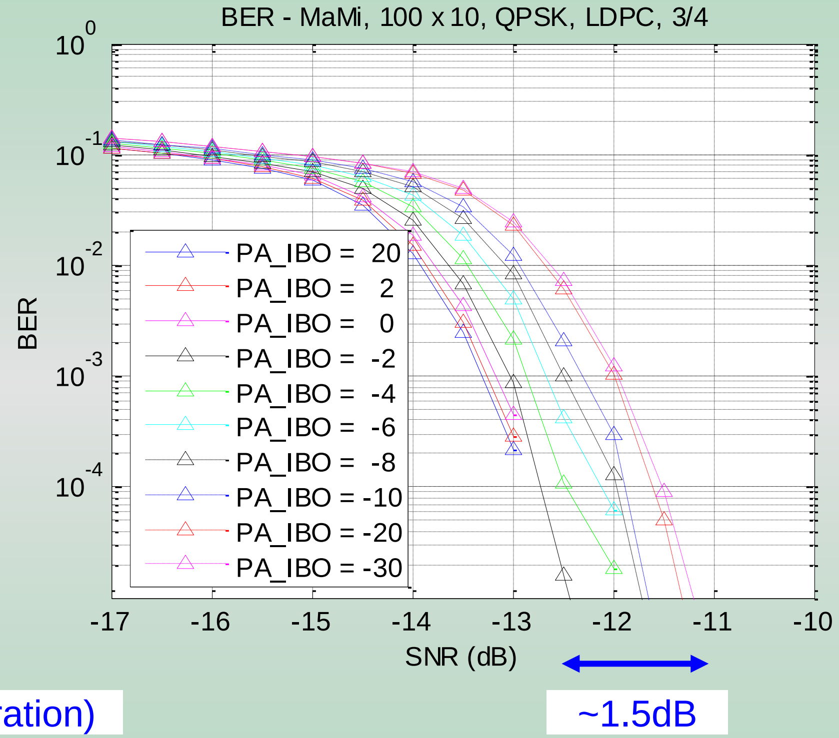
  from 1 dB compression point
  - 20 ≡ linear
  - [2, 0] ≡ moderate saturation
  - [-2, -8] ≡ strong saturation
  - ≤ -10 ≡ complete saturation



Normal (non-Massive) systems typically operate in this back-off zone

Even strong saturation causes limited degradation

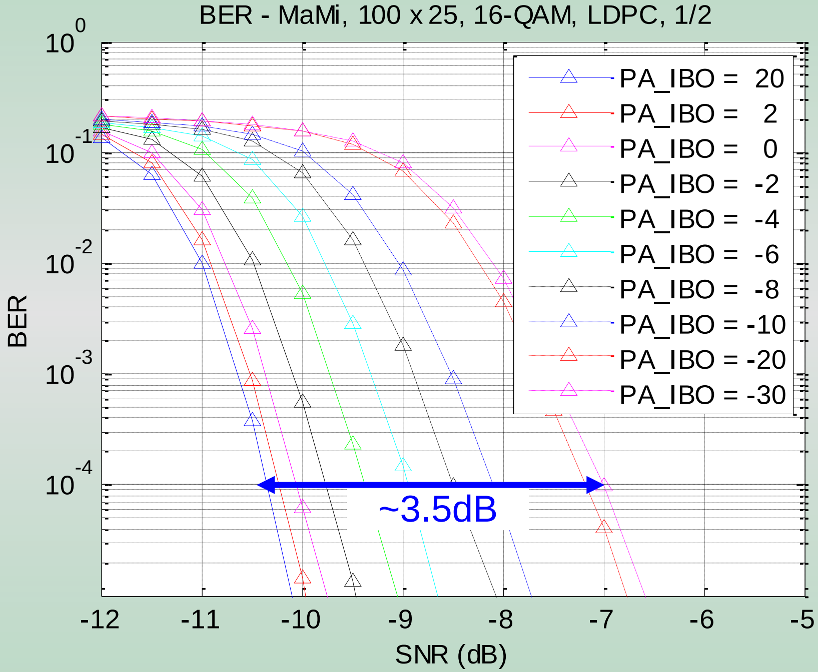


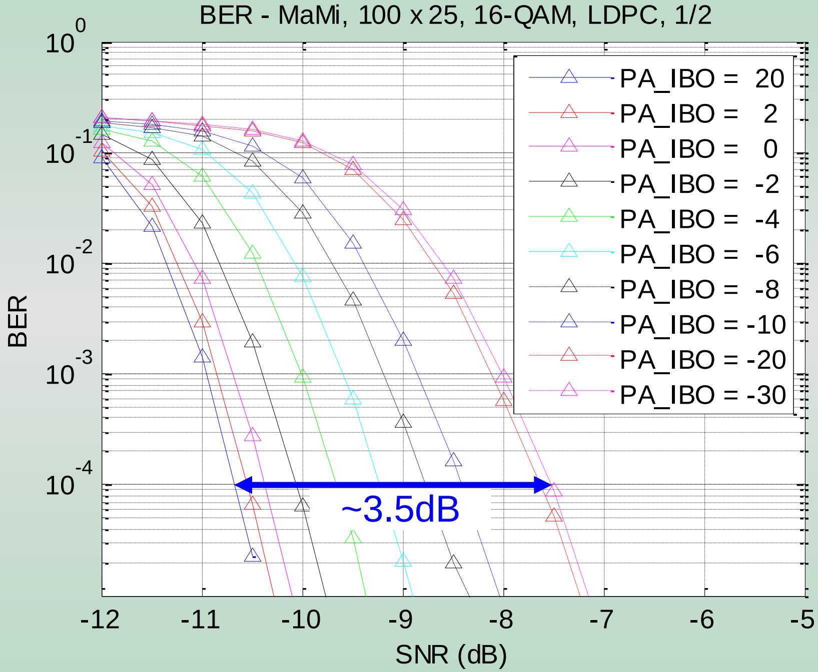


SC
100x10, MRT, QPSK, LDPC 3/4

OFDM
100x10, MRT, QPSK, LDPC 3/4

Even acceptable at very high load



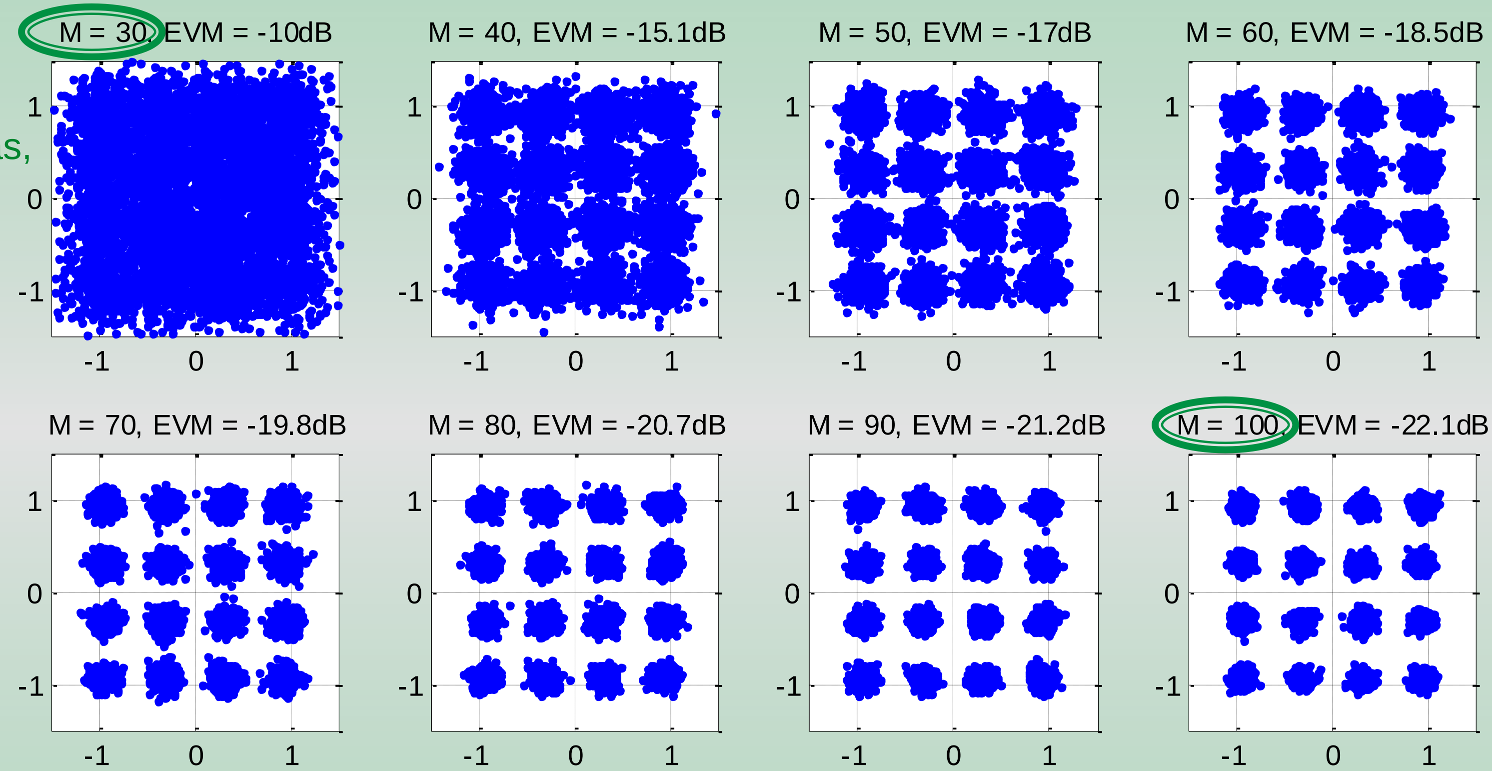


SC
100x25, ZF, 16QAM, LDPC 1/2

OFDM
100x25, ZF, 16QAM, LDPC 1/2

Additional antennas improve EVM

30 antennas,
10 users



100 antennas,
10 users

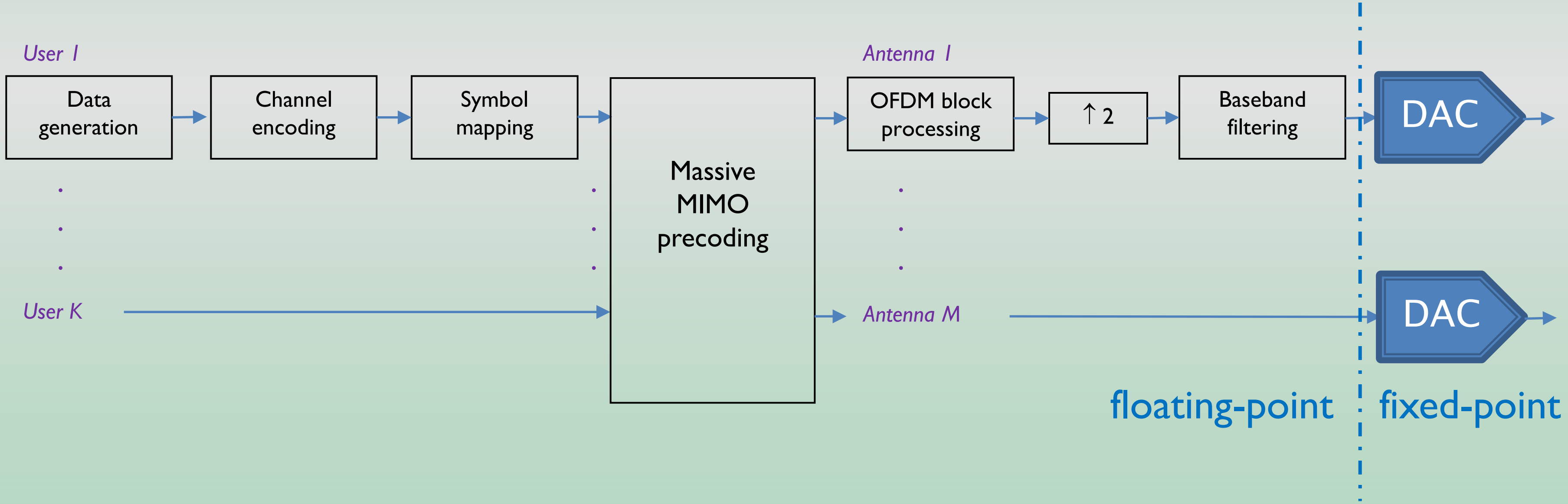
[30:10:100]x10, ZF, 16-QAM

Same total Tx power

0 dB back-off (w.r.t. 1 dB compression)

DAC quantization model: Quantization at the end of digital baseband (Tx)

- Digital processing before fully simulated in floating-point
- Quantization at level of DAC with optimized scaling

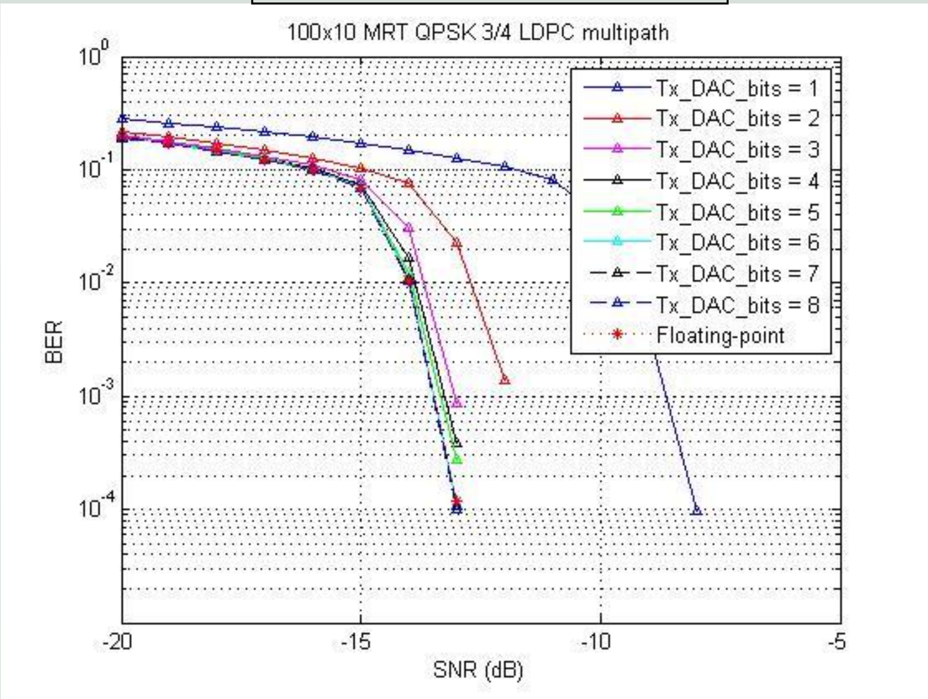


Performance still good with 3 bits

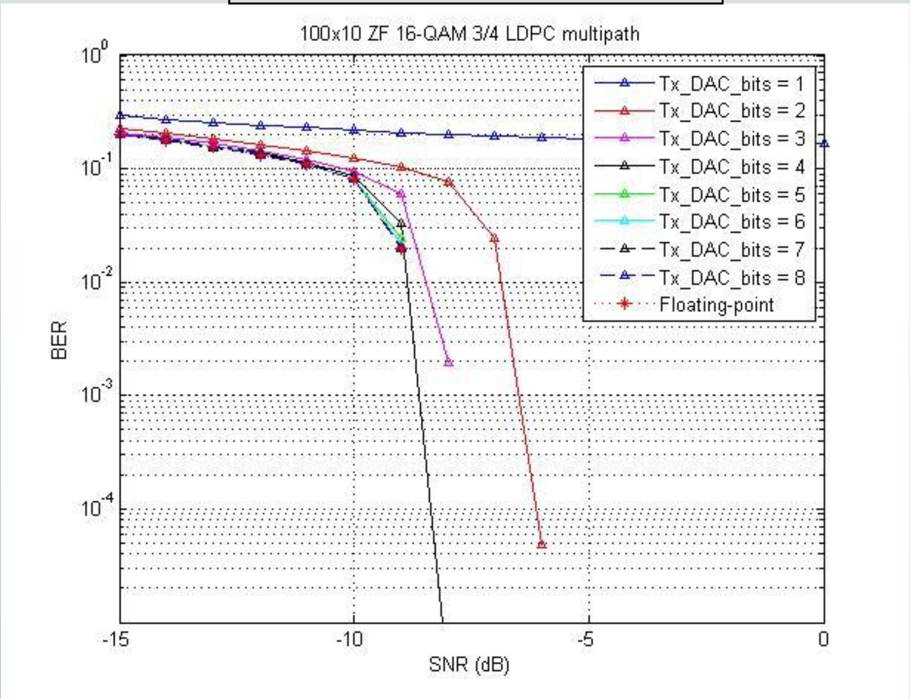
DAC-level quantization tested with 1..8 bits (OFDM MaMi)

100x10 MaMi scenario, multipath Rayleigh, LDPC 3/4

QPSK, MRT precoding



16-QAM, ZF precoding

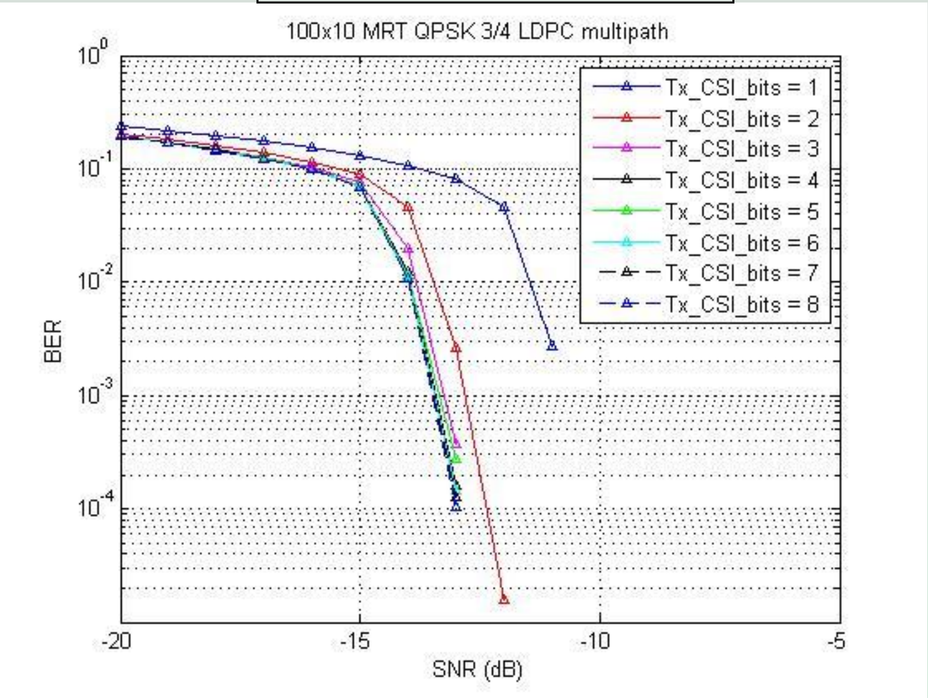


CSI quantization fine with 2 bits

Quantization of channel matrix, used to create precoder

Quantization study on ideal CSI (no uplink-based training)

QPSK, MRT precoding



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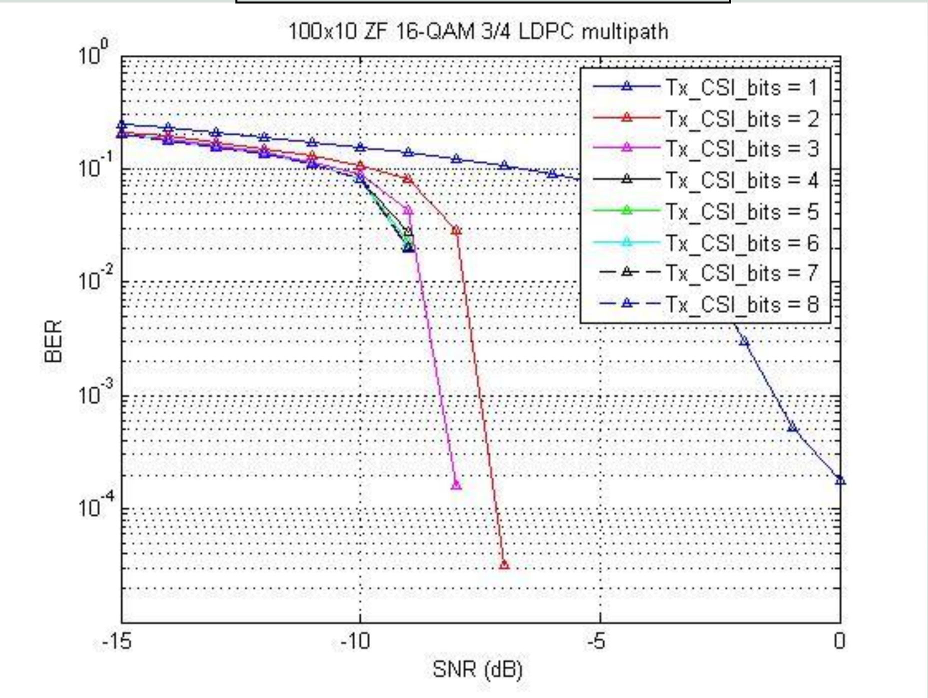
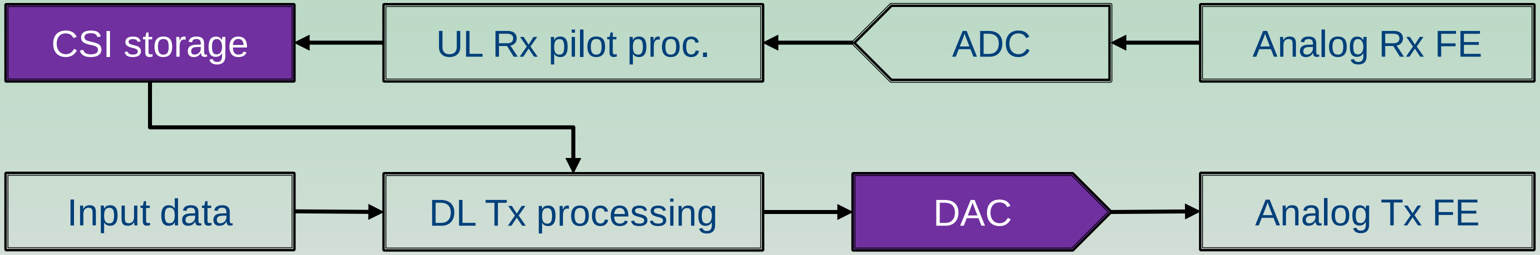
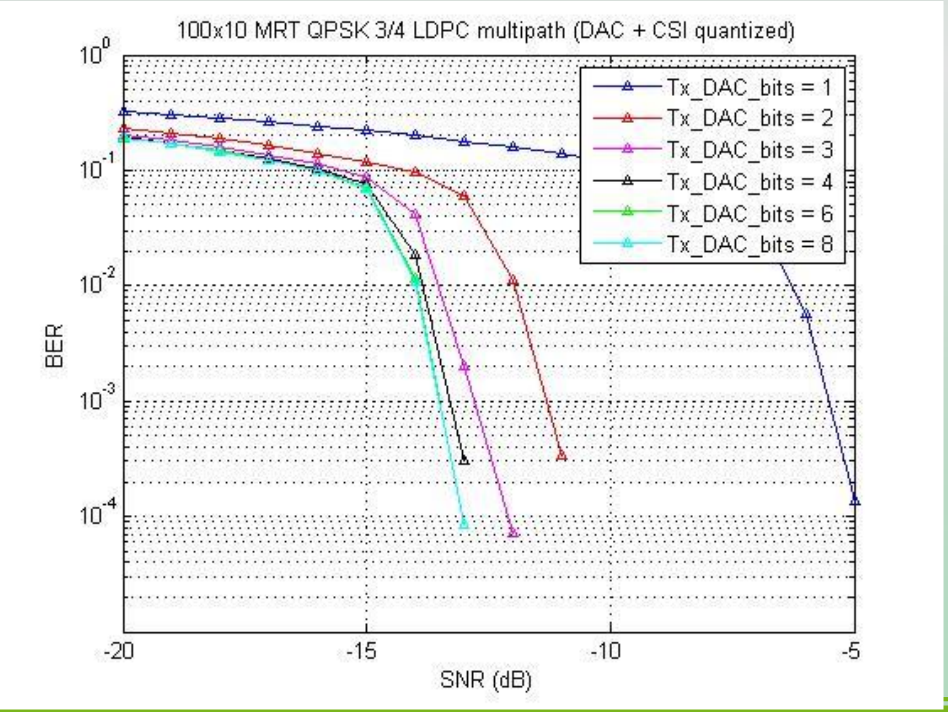


Combined DAC + CSI quantization: Still good performance with 3-bit operation





Computing the power of components

- Main non-PA components (digital baseband, control, analog)
  - Reference power values scaled with scenario parameters, e.g.,
- $P_{Baseband} = \sum_{i \in I_{Baseband}} P_{i,ref} \prod_{x \in X} \left(x_{actual} / x_{ref} \right)^{s_{i,x}}$
  - Scaling parameters
    - Bandwidth
    - Spectral efficiency (constellation and coding rate)
    - Number of antennas
    - System load (frequency-domain)
    - Users = spatial streams (<= antennas)
    - Quantization
  - Additional technology scaling

- Power supply overhead (efficiency-based)
- $P_{Supply} = (P_{PA} + P_{Analog} + P_{Baseband} + P_{Control}) * ((1 + \square_{ACDC})(1 + \square_{DCDC}) - 1)$
- $P_{Total} = P_{PA} + P_{Analog} + P_{Baseband} + P_{Control} + P_{Supply}$

Analog FE power model: what's included

Subcomponent	Downlink [mW]	Uplink [mW]
Predriver	115	0
Modulator	200	0
Frequency synthesis	125	125
Clock generation	75	75
DAC	225	0
LNA	0	125
Mixer	0	200
VGA	0	63
ADC	0	175

Digital and control model: reference in GOPS

- Intrinsic efficiency assumptions: 8 GOPS/W (dedicated hardware)
- Overhead of memories/registers: 2.5x
- Specific functionality and complexity tables (GOPS), adapted for Massive MIMO (precoding, specific channel estimation, simpler compensation of non-idealities...)
- Further reduction of power consumption from quantization (4 bits assumed for Massive MIMO vs. 24 for large and 16 for small cells)

Digital and control model

Subcomponent	Downlink [GOPS]	Uplink [GOPS]	Training [GOPS]
Filtering	6.7	6.7	6.7
Up/Down-sampling	2	2	2
FFT/IFFT	0.5	0.5	0.5
MIMO precoding	.04	.04	0
Synchronization	0	2	0
Channel estimation	0	0	.01
OFDM Mod/Demod	1.3	2.7	2.7
Mapping/Demapping	1.3	2.7	2.7
Channel coding	1.3	8	0
Control	2.7	1	1
Network	8	5.3	0

Counter-intuitive values?

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Scaling to 100x10, QPSK 3/4

[270 Mbps]

- Filtering: 670 GOPS
- MIMO Precoding: 40 GOPS
- OFDM: 270 GOPS
- Demapping: 3 GOPS
- Decoding: 20 GOPS

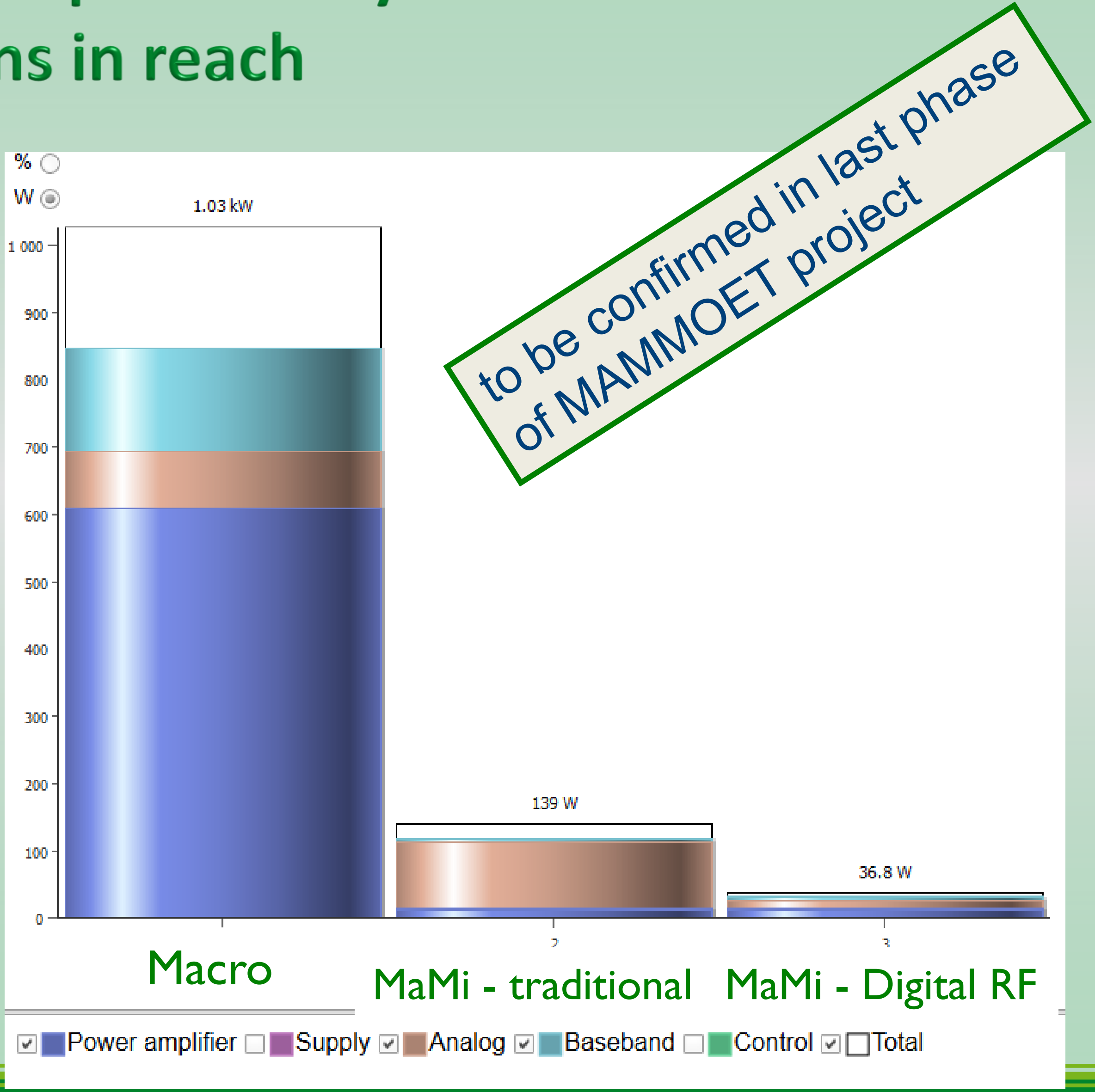
- Precoding: M = 100 CMACs per data symbol ~ 40 GOPS
  - (1 MAC = 1 MUL + 1 ADD => 2 OPS)
- Filtering: (M/K) * 160 CMACs/symbol => ~ 600 GOPS
  - 40-tap filter (MACs), 2x OSF, 2x overhead for shift-registers
  - Room for further reduction of the specs

Massive MIMO has low complexity

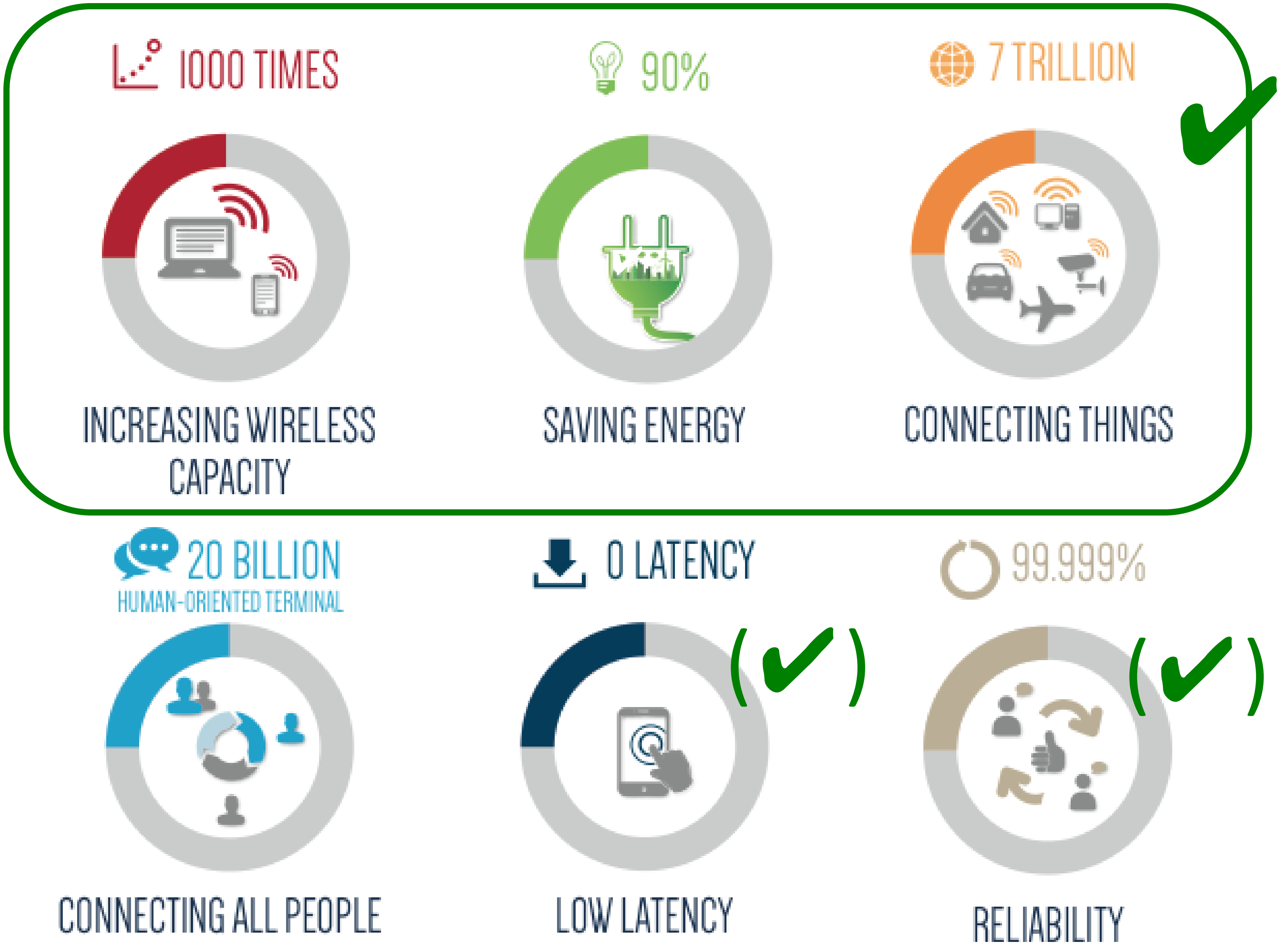
Complexity/energy optimized system: great potential gains in reach

MaMi throughput
- 3x larger

MaMi power
- 7x lower (traditional)
- 27x lower (digital RF)



Massive MIMO: fuelling 5G with a green footprint



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