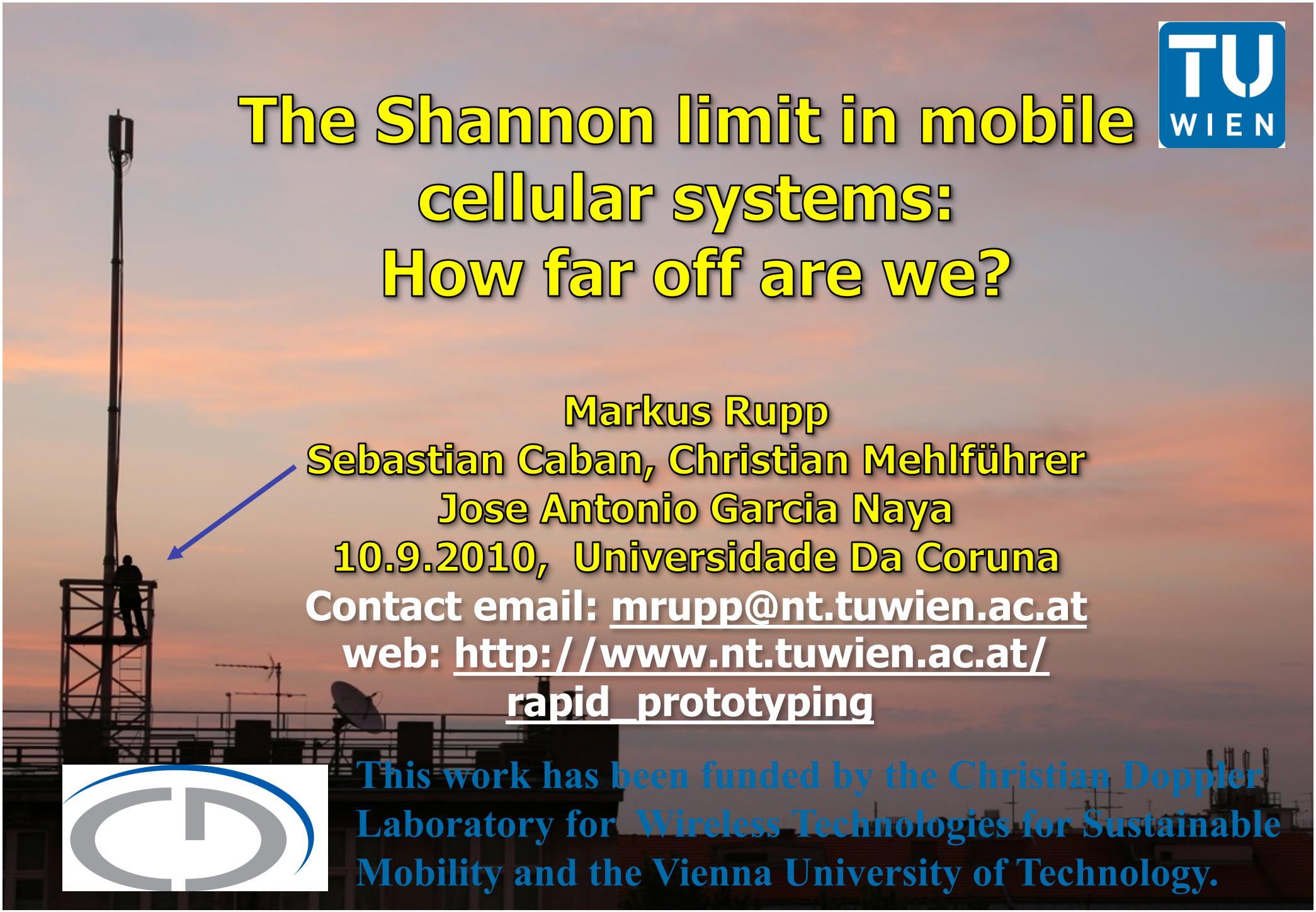

The Shannon limit in mobile cellular systems: How far off are we?

Markus Rupp
Sebastian Caban, Christian Mehlführer
Jose Antonio Garcia Naya

10.9.2010, Universidade Da Coruna

Contact email: mrupp@nt.tuwien.ac.at
web: http://www.nt.tuwien.ac.at/rapid_prototyping

This work has been funded by the Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility and the Vienna University of Technology.

Outline

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- **WiMAX Measurements**
  - **IEEE 802.16-2004 (Section 8.3) with OFDM physical layer**
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- **Comparisons HSDPA vs. WiMAX**
- **Conclusion**

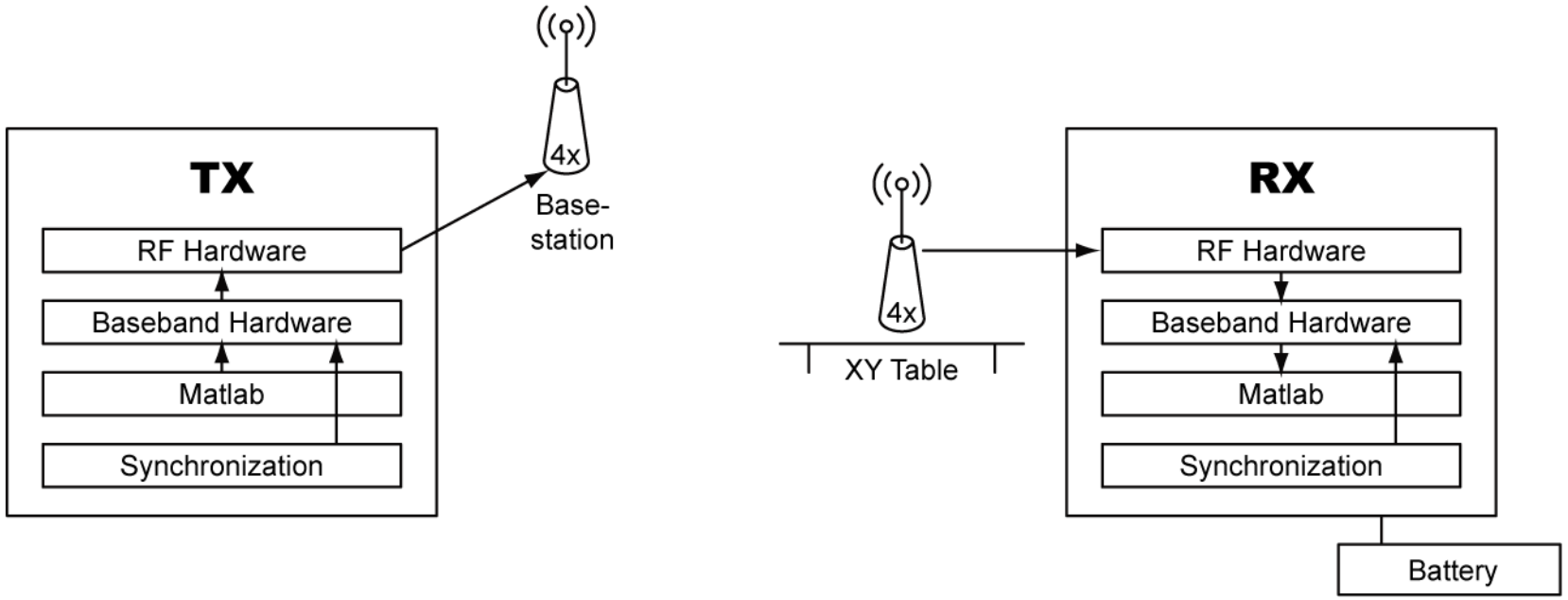
Evaluating MIMO radio communication

- theoretically
- by pure simulation
- by channel sounding
- utilizing a testbed
- utilizing a prototype
- using the final product

degree of realism

effort

MIMO Testbed [T1,T2]

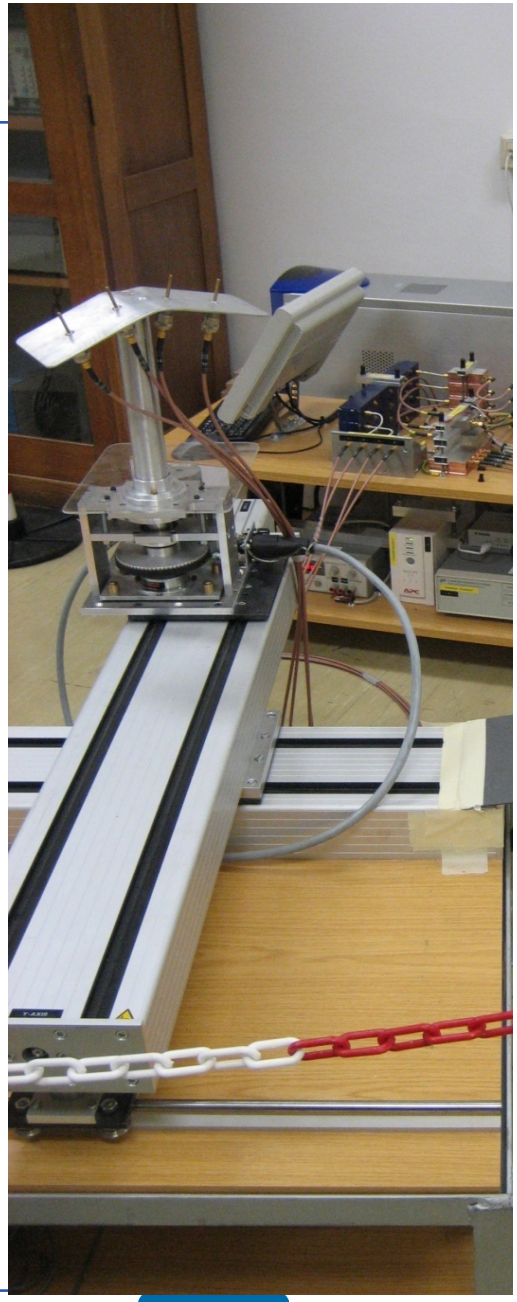


Data is created and evaluated in Matlab ...

Number of Antennas: 4x4
Bandwidth: 5 MHz
Center Frequency: 2.5 GHz

MIMO Testbed [T1,T2]

- **MIMO WiMAX 802.16-2004**
  - **OFDM physical layer**
    - **including channel coding and decoding**
    - **SISO and MIMO**
- **MIMO HSDPA (TxAA, DTxAA)**
  - **CDMA physical layer**
    - **including channel coding and decoding**
    - **SISO and MIMO**
- **MIMO LTE (new)**



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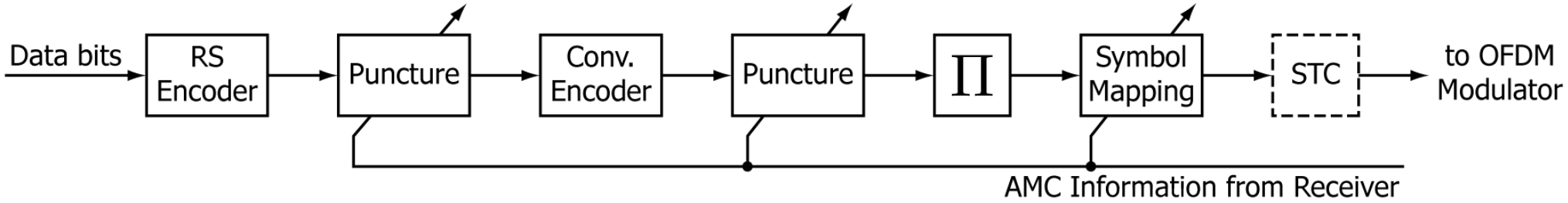
Adaptive Modulation and Coding (AMC)

- **Encoding**
  - **concatenated Reed-Solomon / convolutional code**
  - **puncturing depending on AMC information**
  - **optional block/convolutional turbo coding**
  - **Alternatively: LDPC coding**
- **Adaptive symbol mapping**
- **Optional Alamouti space-time coding**

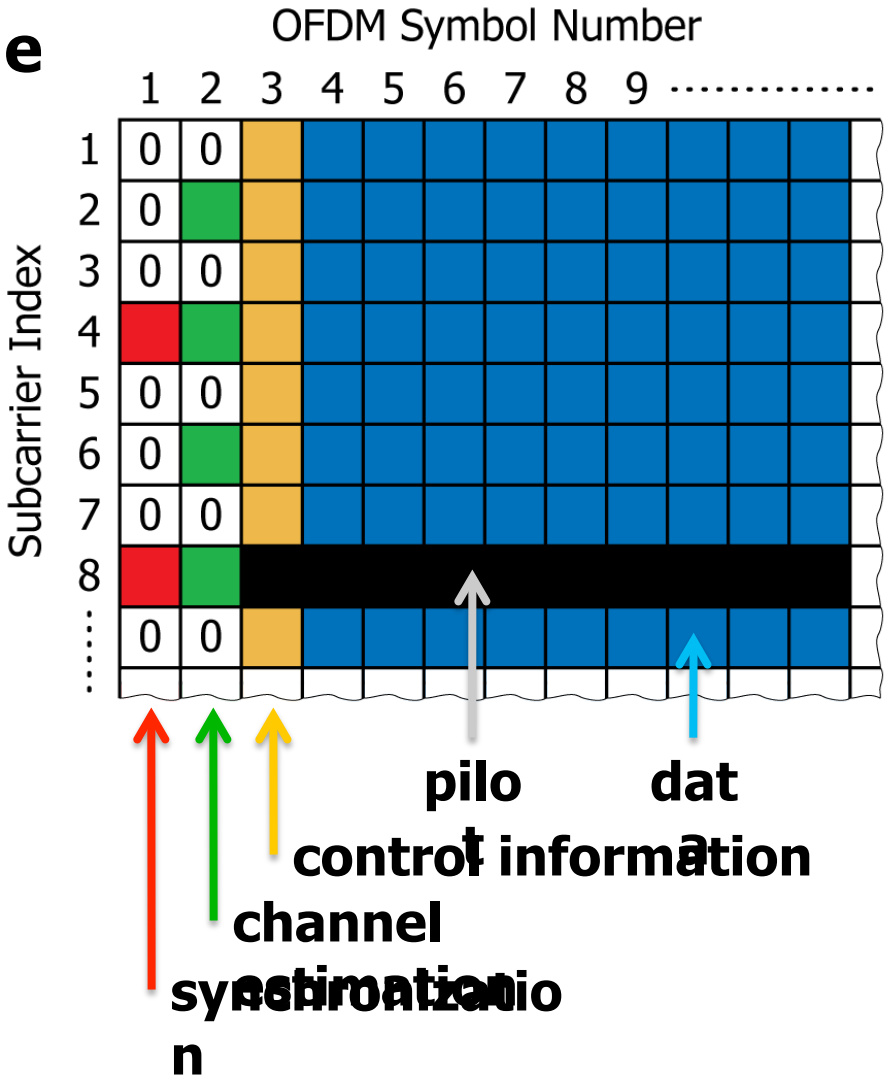


Coding and Modulation

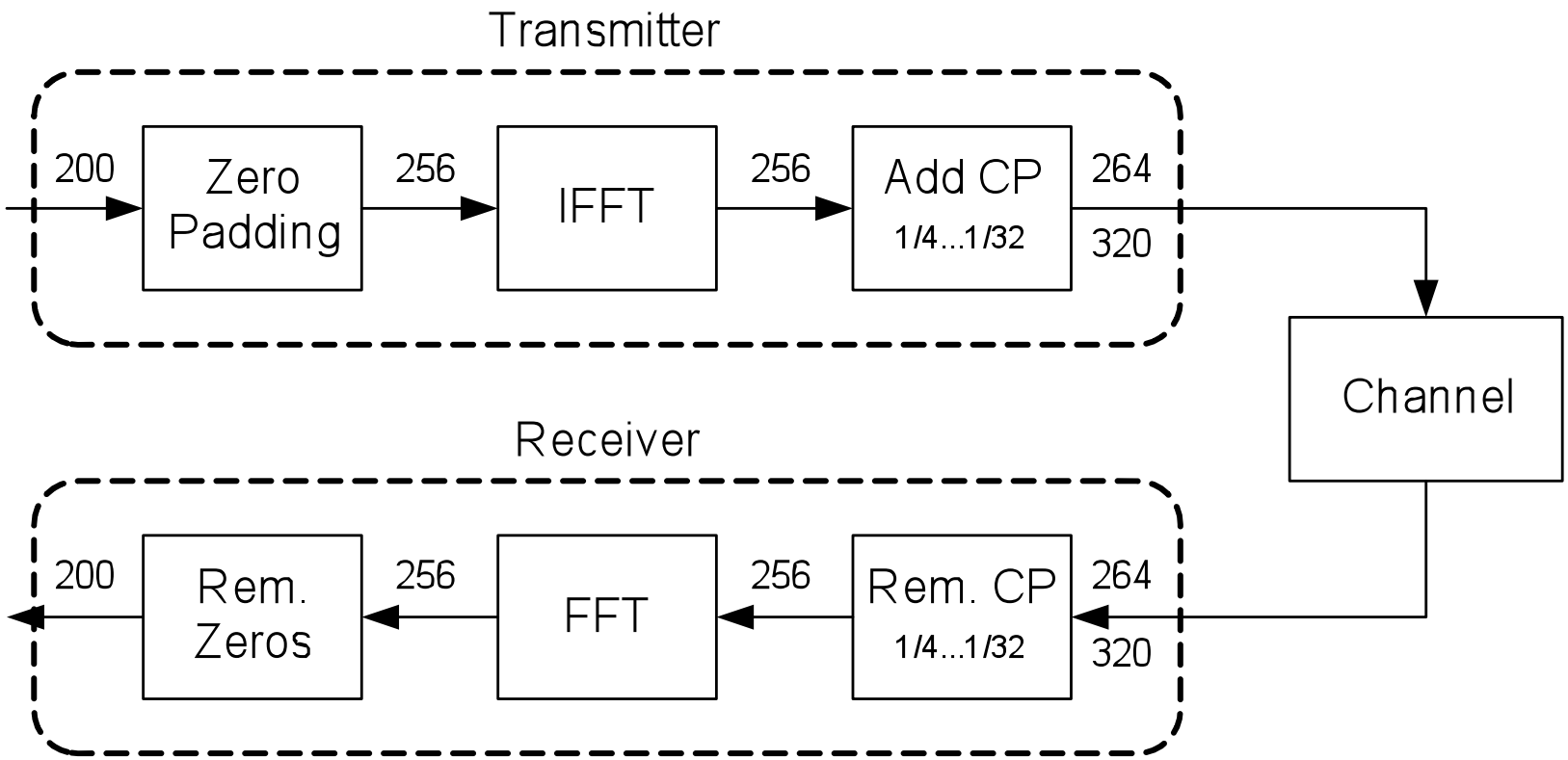
AMC value	Modulation	RS Code Rate	CC Rate	Overall Code Rate
1	2-PAM	1	1/2	1/2
2	4-QAM	3/4	2/3	1/2
3	4-QAM	9/10	5/6	3/4
4	16-QAM	3/4	2/3	1/2
5	16-QAM	9/10	5/6	3/4
6	64-QAM	8/9	3/4	2/3
7	64-QAM	9/10	5/6	3/4

OFDM Frame Structure

- **3 OFDM symbols preamble**
  1. **Synchronization**
  2. **Channel estimation**
  3. **Control information**
- **Subcarrier distribution**
  - **192 data subcarriers**
  - **8 pilot subcarriers**
  - **1 zero DC subcarrier**
  - **55 guard band subcarriers**
  - **$\rightarrow$ 256 total**



OFDM Modulation and Demodulation

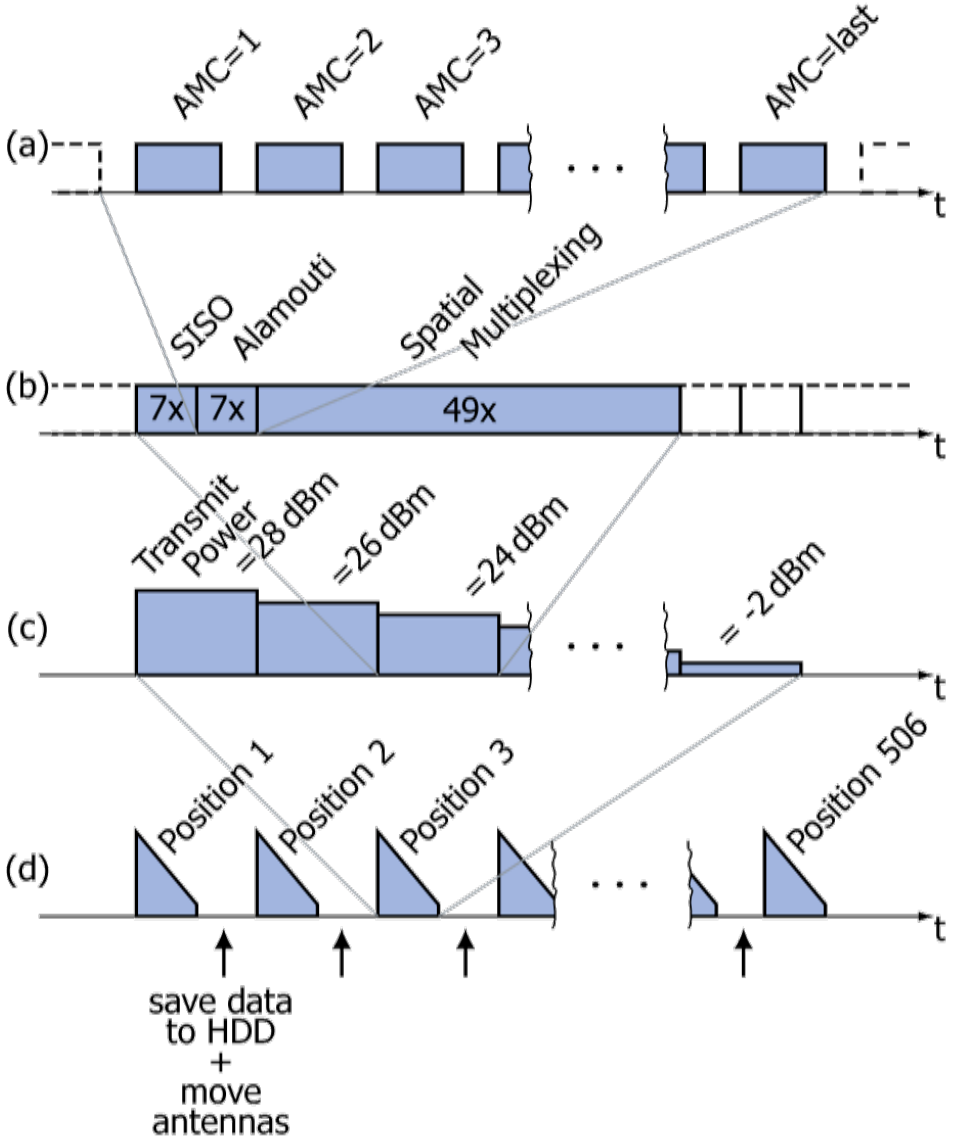


Preliminary Measurement Setup [W2]

- **3 scenarios**
  1. **NLOS, outdoor-to-indoor**
  2. **NLOS, outdoor-to-outdoor**
  3. **LOS, outdoor-to-indoor**
- **Parameters**
  - **5 MHz channel bandwidth**
  - **Cyclic prefix 1/4**
  - **192 carrier OFDM**
  - **Rx antenna distance 1.2λ**
  - **Tx antenna distance: 2.75λ**
  - **Tx antenna height: 16m**

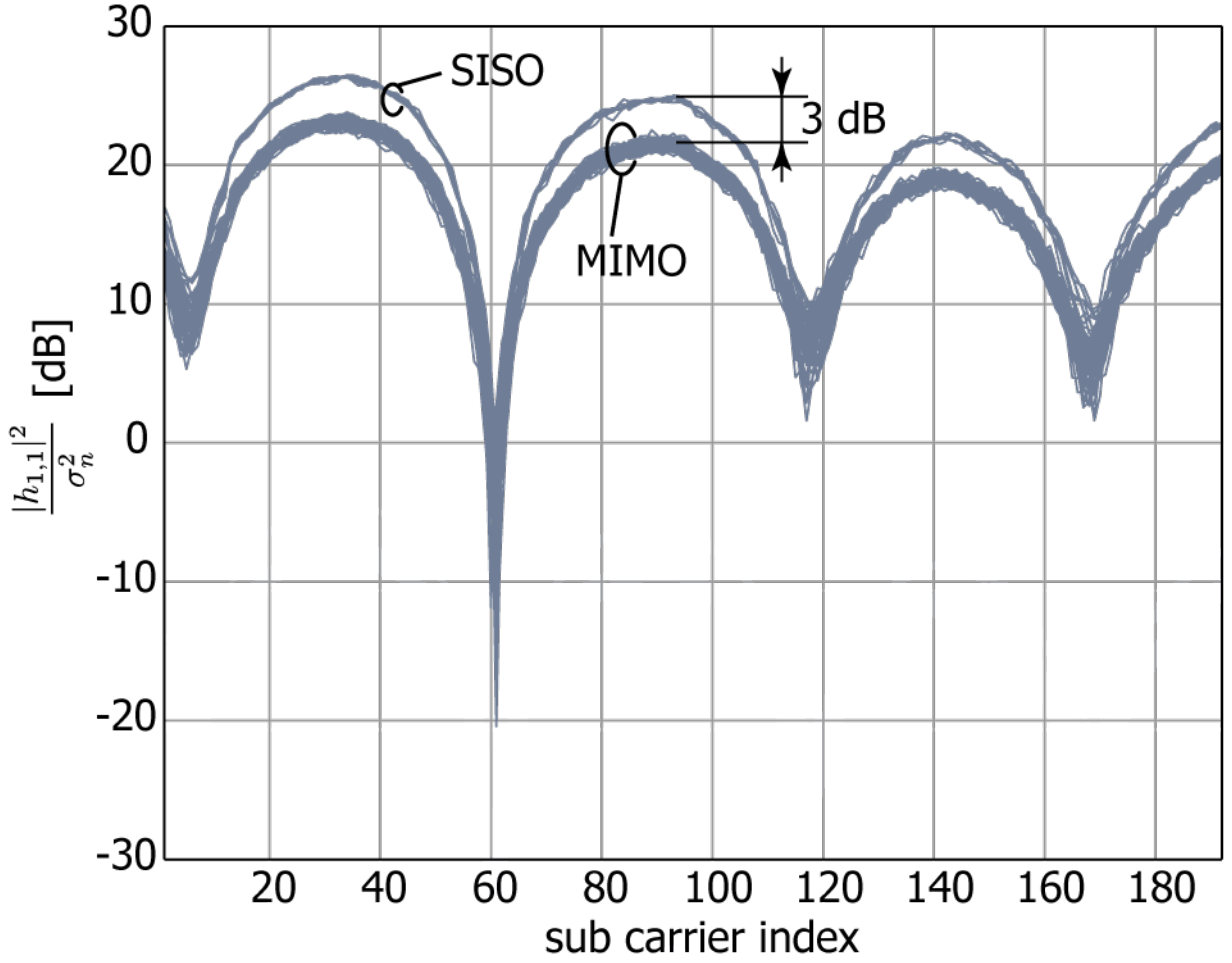
Measurement distance: 50-100m

Block Transmission [W2]



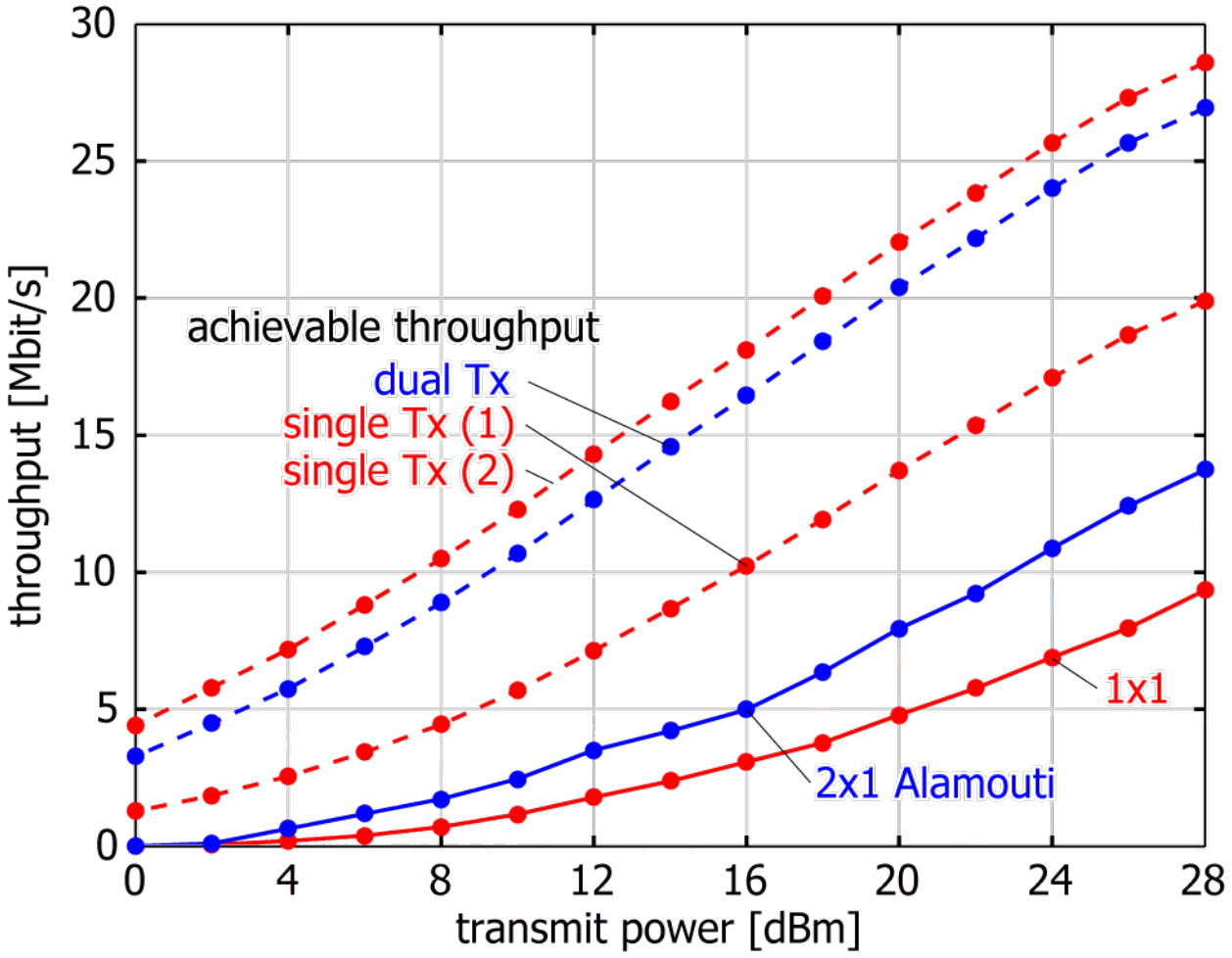
1. **SIMO, 7 AMC schemes, 3 bit feedback**
2. **MIMO with Alamouti, 7 AMC schemes, 3 bit feedback**
3. **MIMO with spatial multiplexing, same coding scheme on both antennas, 3 bit feedback**
4. **MIMO with spatial multiplexing, individual coding schemes on both antennas, 6 bit feedback**

Measured Channel Coefficients [W2]

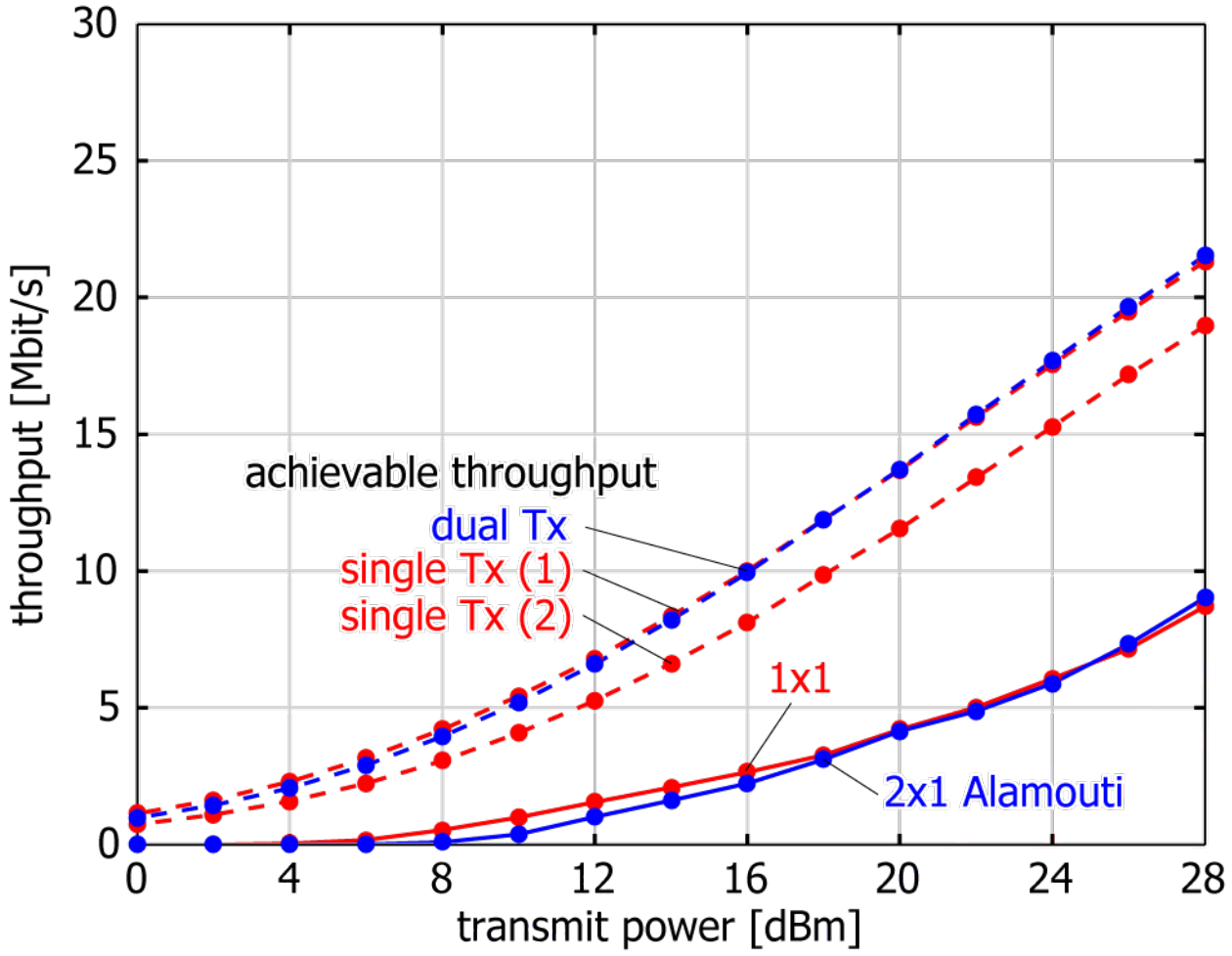


Duration of measurements: ~200ms

One Receive Antenna: NLOS outdoor-to-outdoor [W2]



One Receive Antenna: NLOS outdoor-to-indoor [W2]

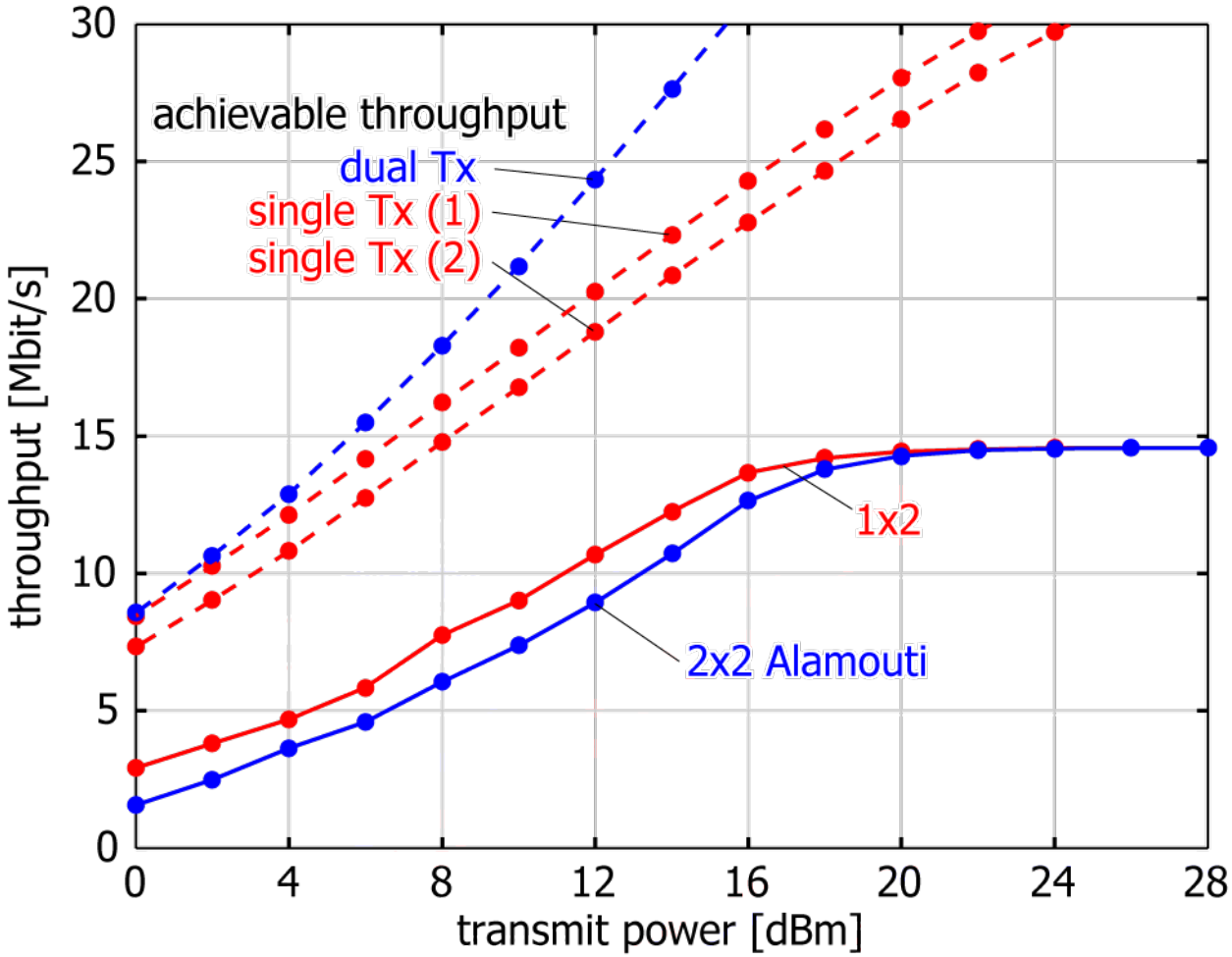


One Receive Antenna: Conclusions [W2]

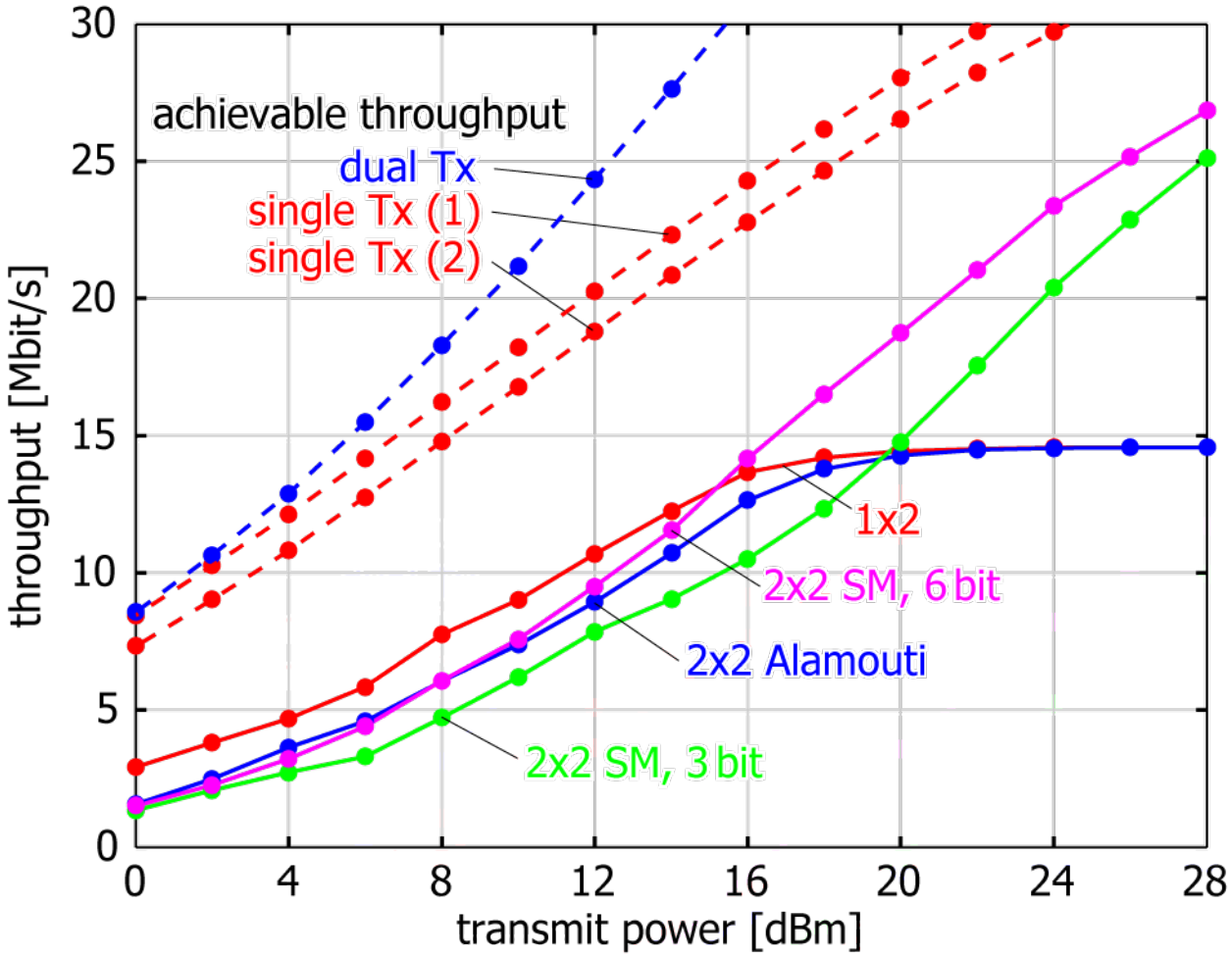
- **The measured scenarios behave asymmetric with respect to the transmit antenna**
- **If channel is known at the transmitter, antenna selection can improve the performance**
- **Alamouti looses (slightly) compared to single antenna transmission**
  - **more sensitive channel estimation errors**
  - **3dB less power for training**
  - **Asymmetric scenario**

- **Huge gap of >10 dB between measured and achievable throughput!**

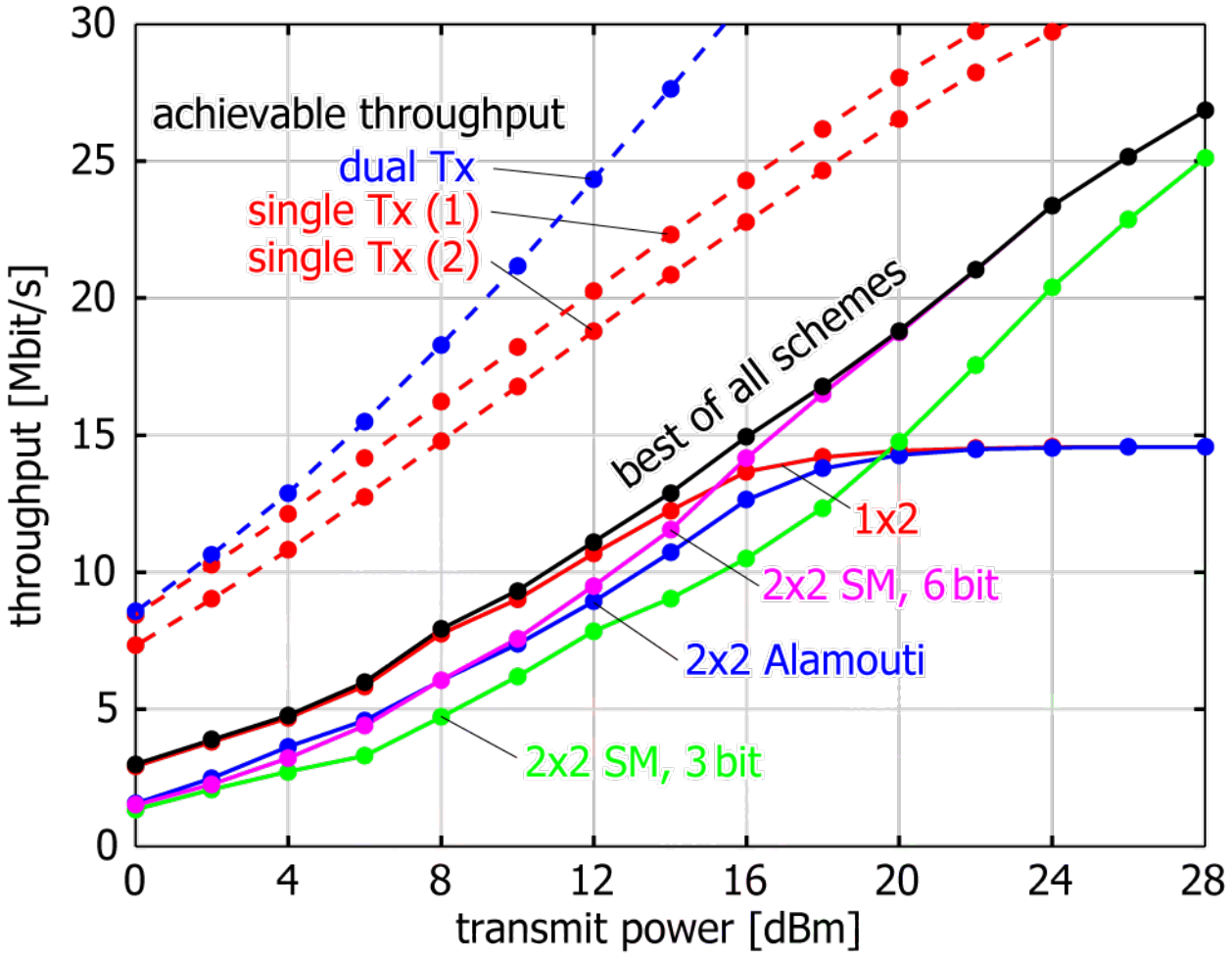
Two Receive Antennas MRC: LOS outdoor-to-indoor [W2]



Two Receive Antennas: LOS outdoor-to-indoor [W2]



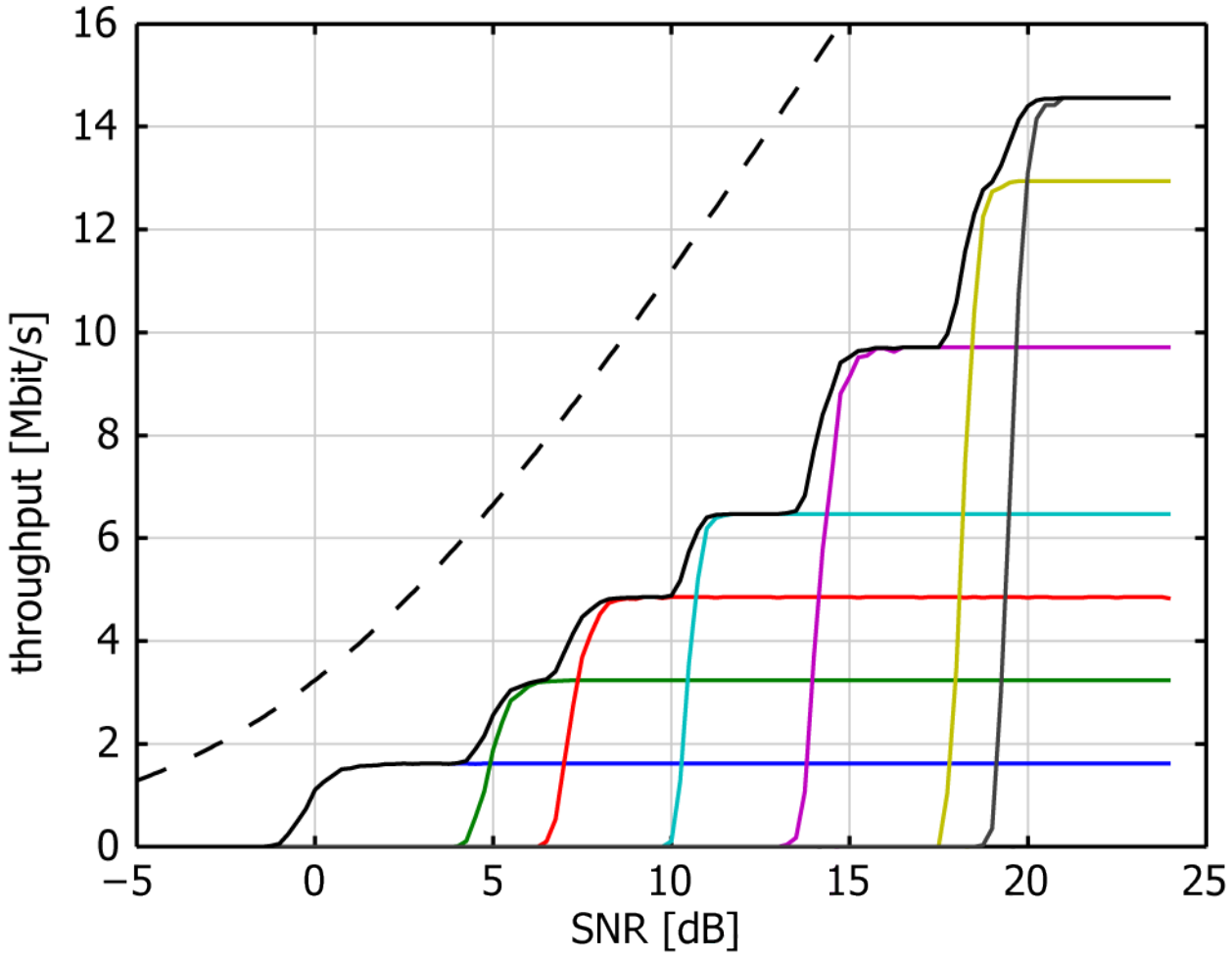
Two Receive Antennas: LOS outdoor-to-indoor [W2]



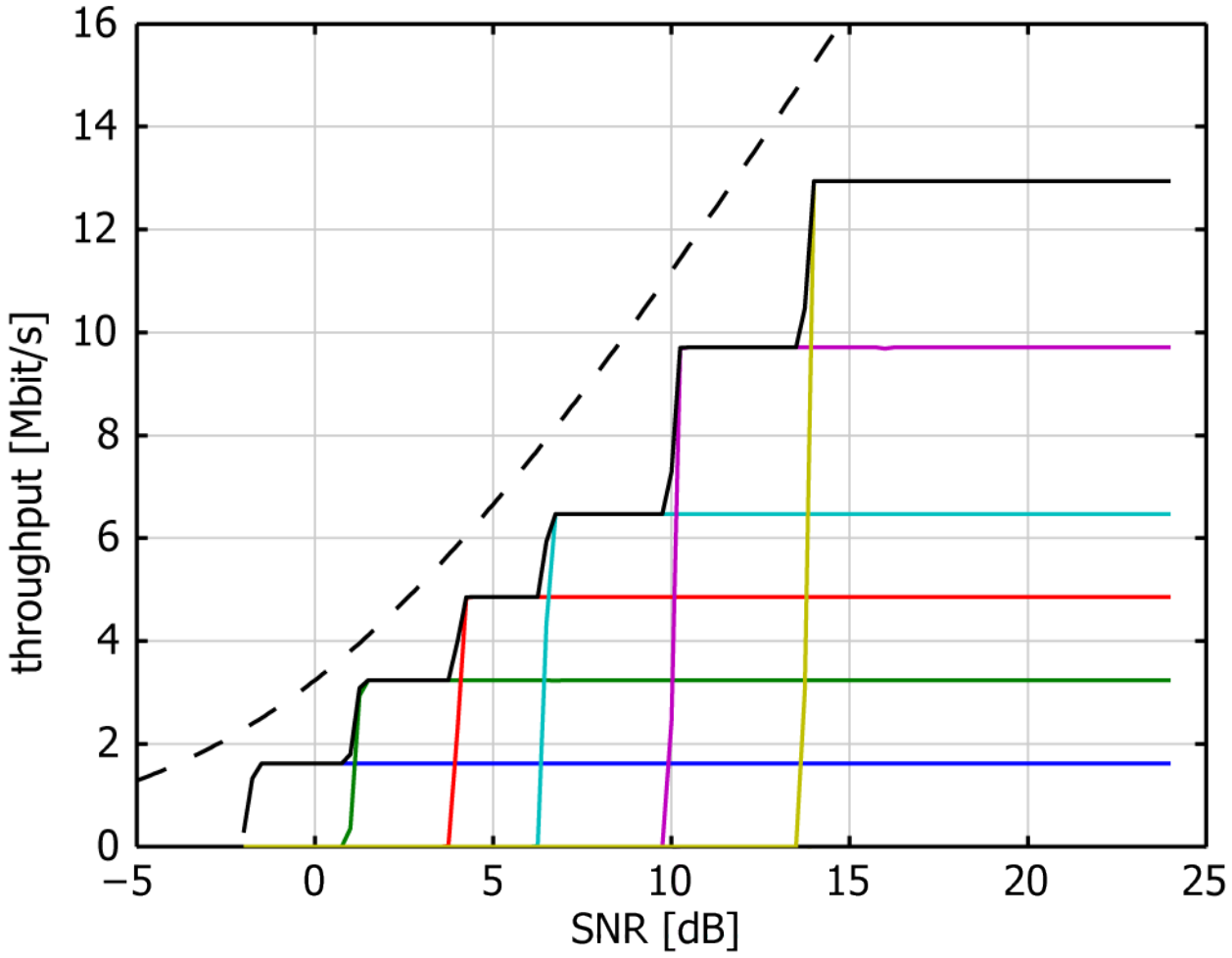
Two Receive Antennas: Conclusions [W2]

- **Spatial multiplexing with 6 bit feedback outperforms spatial multiplexing with 3 bit feedback**
  - **The 6 bit feedback allows to exploiting the asymmetric channels**
- **Alamouti is better than spatial multiplexing with 3 bit feedback due to transmit diversity**
- **Still, a huge gap of >10 dB between measured and achievable throughput is observed!**
- **Enhancements**
  - **Better channel coding**
    - **e.g. Low Density Parity Check (LDPC) codes**
  - **Enhanced channel estimation techniques**
    - **e.g. LMMSE channel estimation to exploit correlation between subcarriers**

AWGN Performance of the Reed Solomon-Conv.Coder



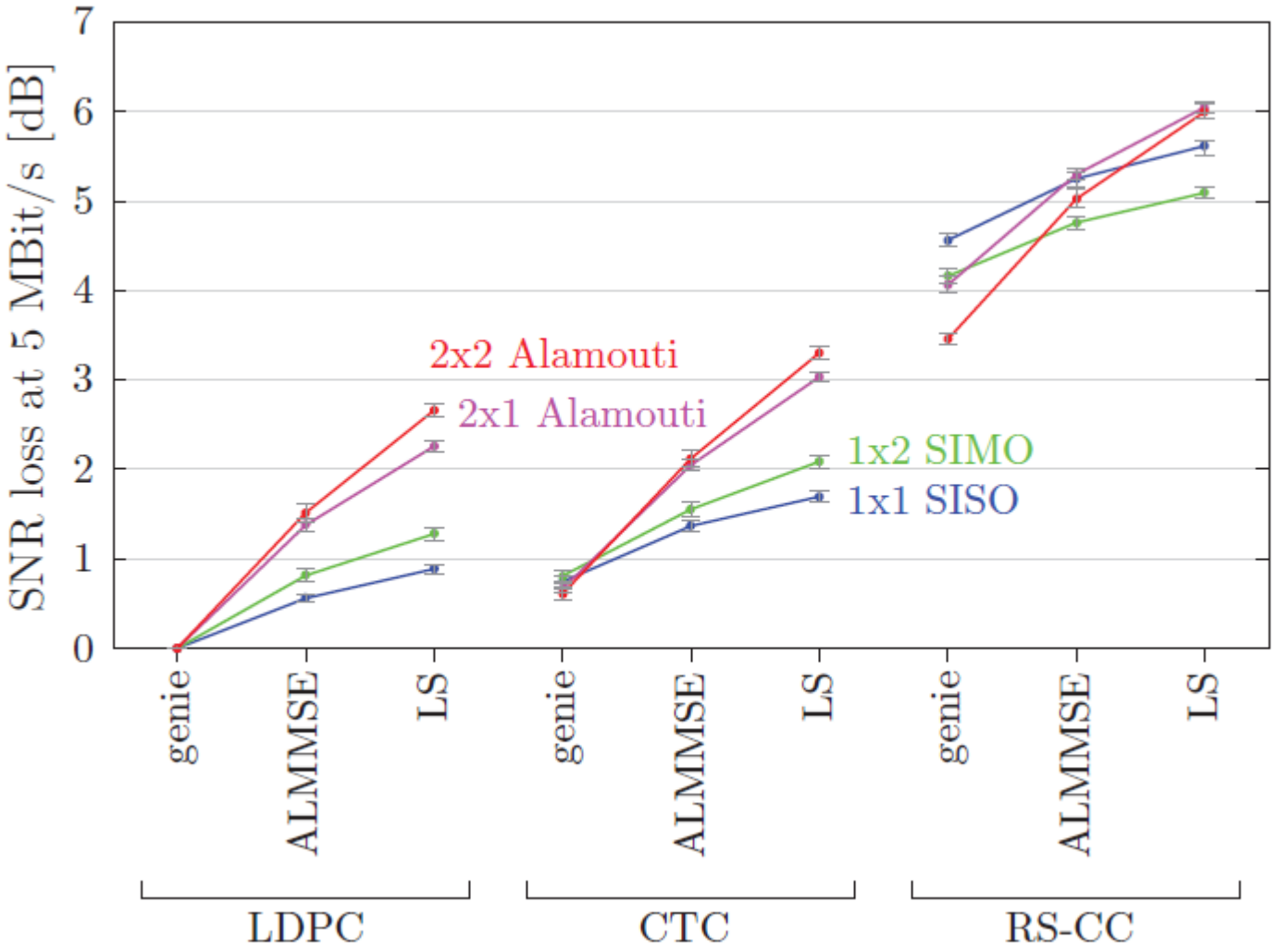
AWGN Performance of LDPC codes



SNR Gain of Improved Channel Estimators over the LS Estimator [W1]

Scenario 1	LMMSE	genie-driven
1x1 SISO	0.6 dB	1.2 dB
2x1 Alamouti	1.8 dB	2.9 dB
1x2 SIMO	0.5 dB	1.2 dB
2x2 Alamouti	1.9 dB	3.2 dB
2x2 Spatial Multiplexing (3 bit)	1.4 dB	2.4 dB
2x2 Spatial Multiplexing (6 bit)	1.1 dB	2.2 dB

Losses in WiMAX



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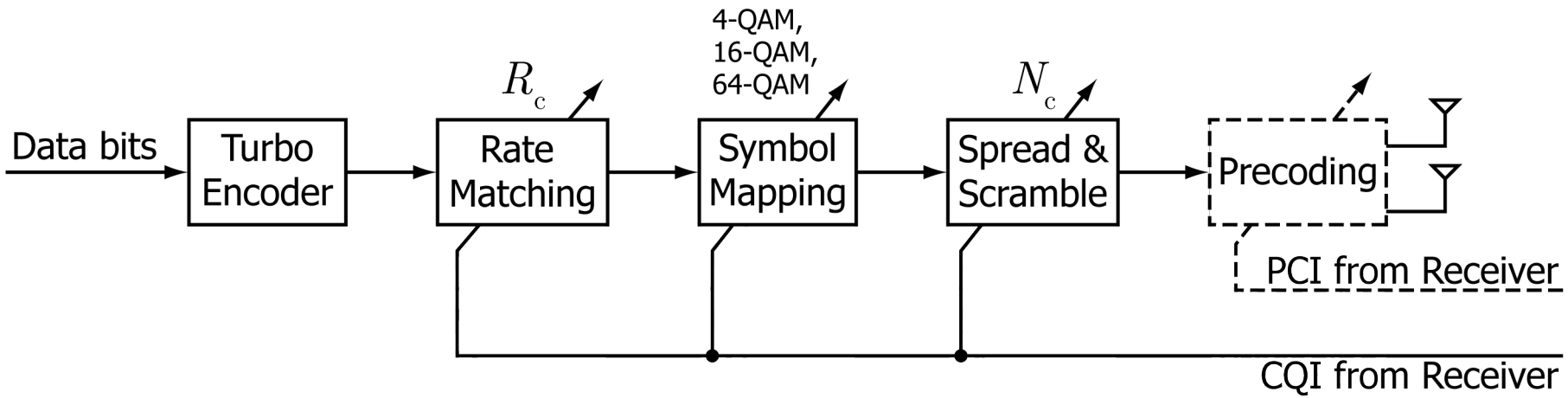
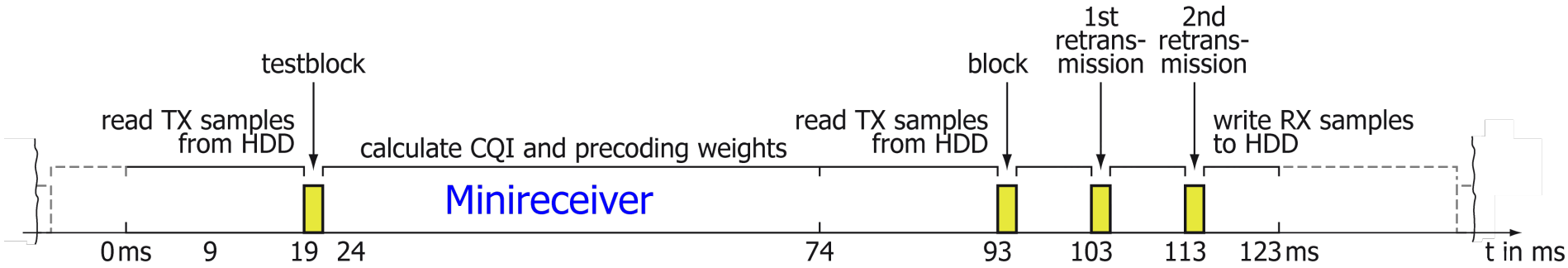
HSDPA Overview



- **Channel adaptation is performed by means of**
  - **a Channel Quality Indicator (CQI) and**
  - **a Precoding Control Indicator (PCI) when two transmit antennas are available**

Transmission Timing [H4]



- **Large number of possible transmit blocks require channel evaluation at the receiver**
- **Minireceiver estimates channel and noise and calculates the CQI and PCI**

SINR Estimation in Minireceiver [H5]

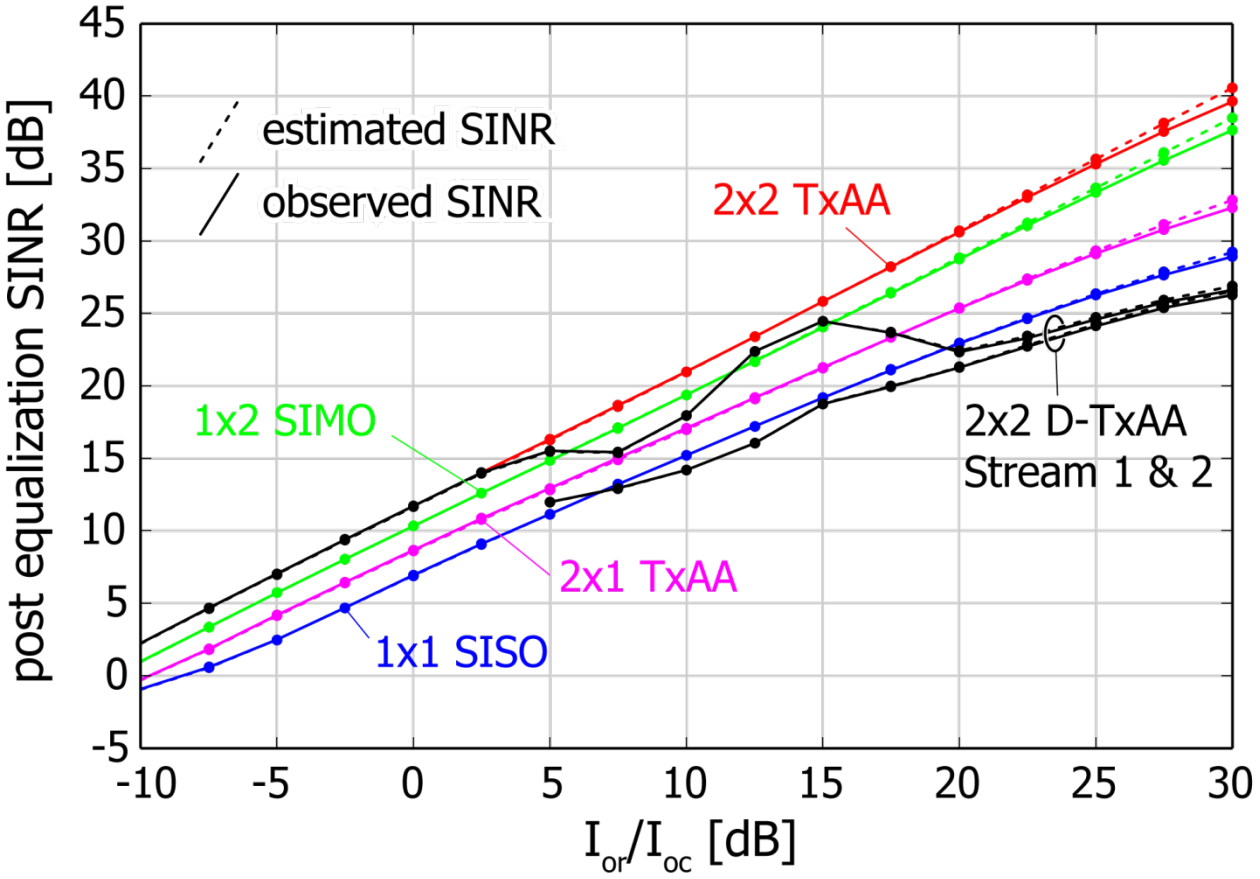
$$\mathrm{SINR}_{\mathrm{est}} = \frac{P_s}{\sigma_{n'}^2 + P_{\mathrm{ISI}} + P_{\mathrm{INT}}}$$

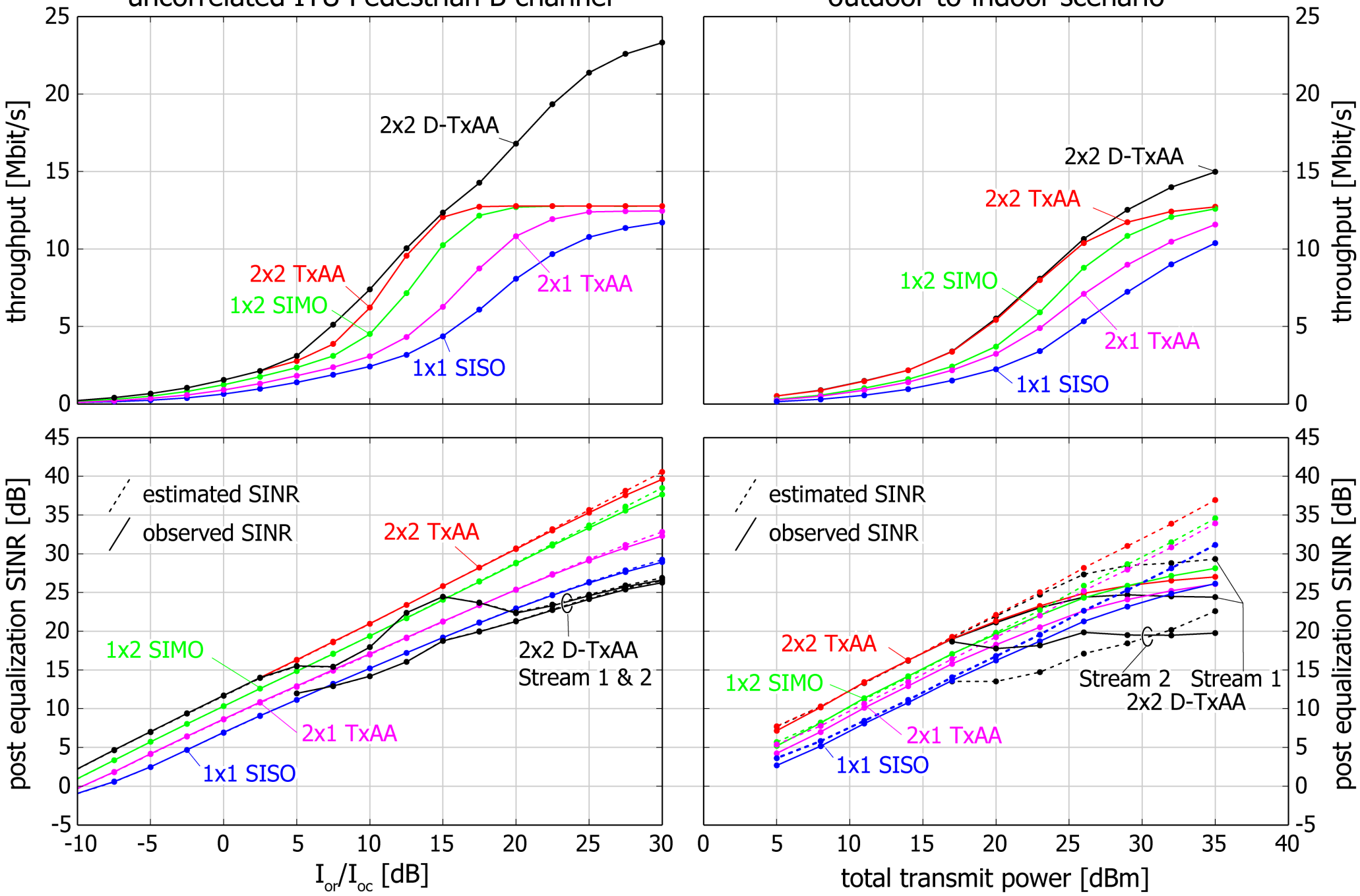
The post equalization SINR is given by

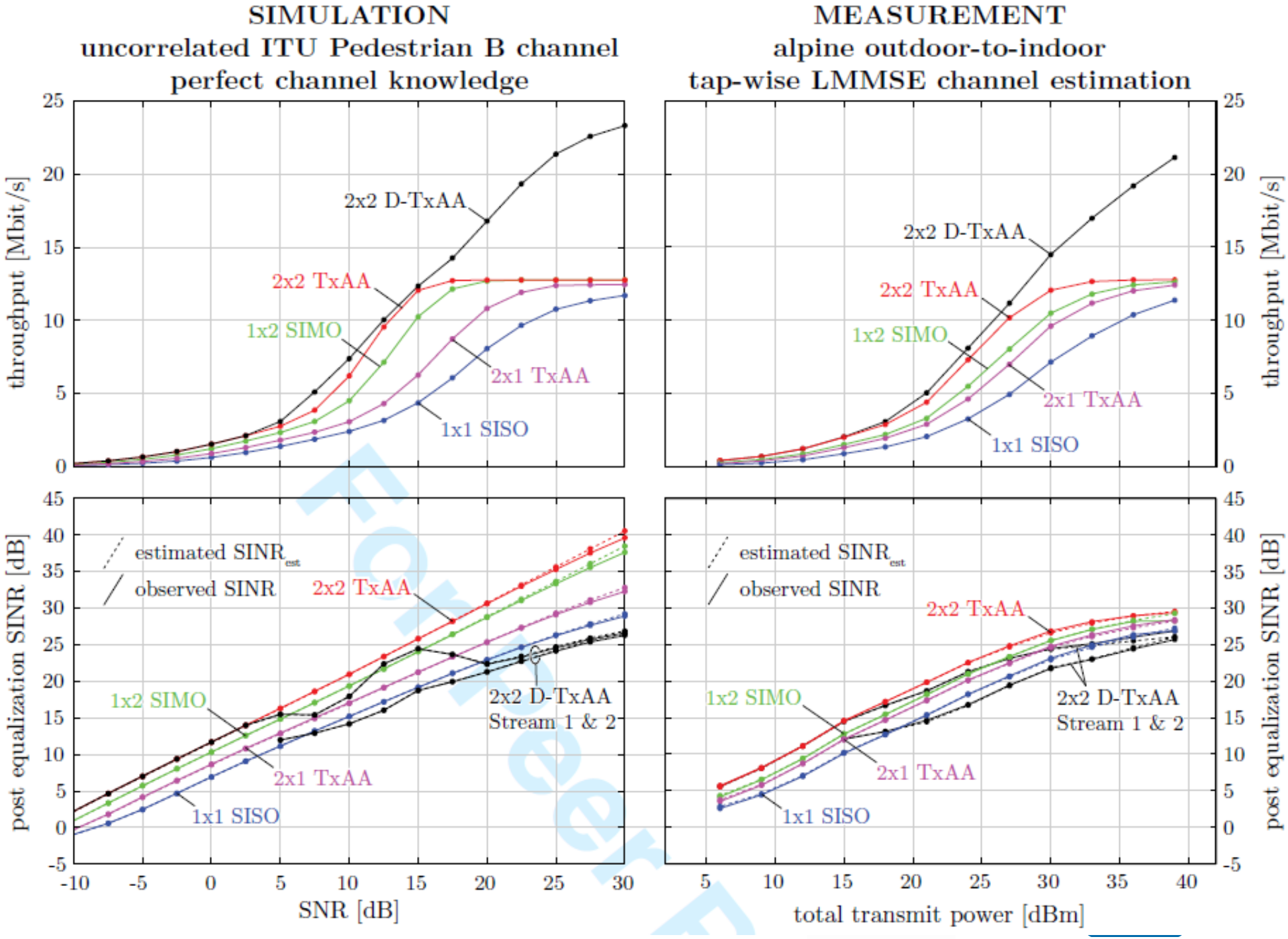
- **the signal power** P_s
- **the noise at the output of the equalizer** $\sigma_{n'}^2$
- **the remaining inter-symbol interference** P_{ISI}
- **the interference caused by spatially multiplexed streams sharing the same scrambling and spreading codes** P_{INT}

SINR is calculated for all possible precoding vectors and mapped to the supported CQI values. The precoding vector maximizing the transport block size is selected.

Verification of the SINR Estimation in the Simulation [H5]




SIMULATION
uncorrelated ITU Pedestrian B channel
MEASUREMENT
outdoor-to-indoor scenario
throughput [Mbit/s]
2x2 D-TxAA
2x2 TxAA
1x2 SIMO
2x1 TxAA
1x1 SISO
post equalization SINR [dB]
estimated SINR
observed SINR
2x2 D-TxAA
Stream 1 & 2
Stream 2
Stream 1
I_{or}/I_{oc} [dB]
total transmit power [dBm]


SIMULATION
uncorrelated ITU Pedestrian B channel
perfect channel knowledge
MEASUREMENT
alpine outdoor-to-indoor
tap-wise LMMSE channel estimation
throughput [Mbit/s]
2x2 D-TxAA
2x2 TxAA
1x2 SIMO
2x1 TxAA
1x1 SISO
post equalization SINR [dB]
estimated SINR est
observed SINR
2x2 D-TxAA
Stream 1 & 2
SNR [dB]
total transmit power [dBm]

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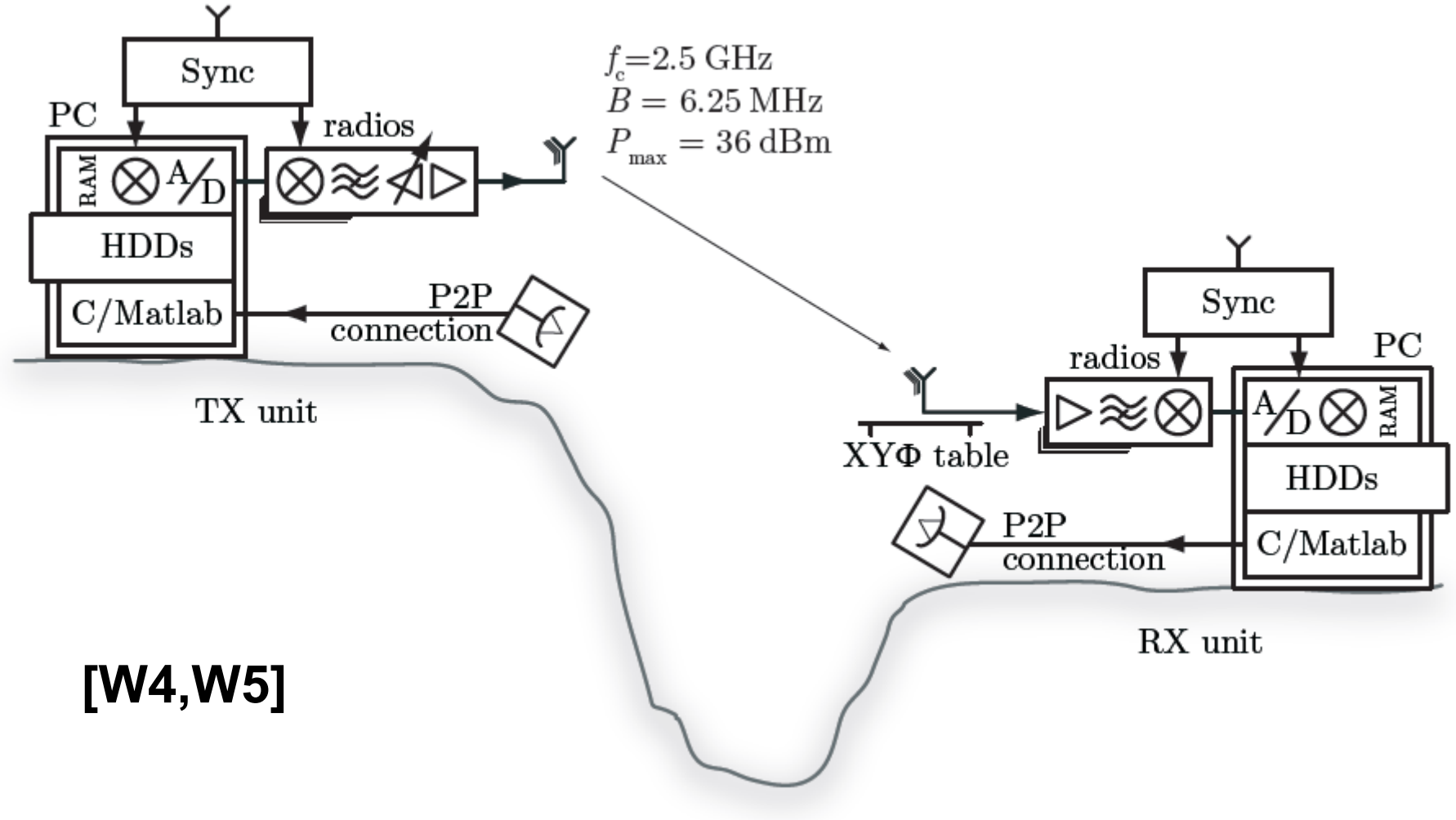
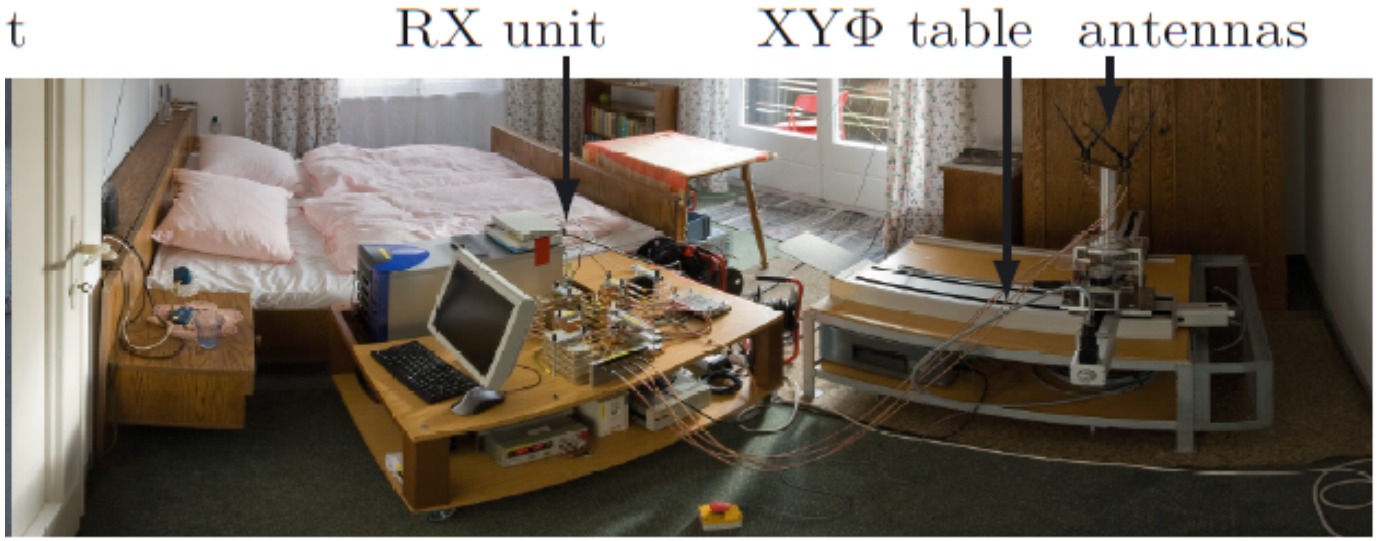
Two Measurement Campaigns: Alpine and Urban



[W4,W5]

Two Measurement Campaigns: Alpine and Urban



Two Measurement Campaigns: Alpine and Urban

[C1,C2,C3,C4,C5]

Channel Capacities

Capacity (Shannon)

$$C(P_{\mathrm{Tx}}) = \max_{\sum \mathrm{tr}\{\mathbf{R}_k\} \leq K} \frac{B}{K} \sum_{k=1}^{K} \log_2 \det \left(\mathbf{I} + \frac{P_{\mathrm{Tx}}}{\sigma_{\mathrm{n}}^2 N_{\mathrm{T}}} \mathbf{H}_k \mathbf{R}_k \mathbf{H}_k^{\mathrm{H}} \right)$$

Mutual Information (constrained capacity)

$$I(P_{\mathrm{Tx}}) = \frac{B}{K} \sum_{k=1}^{K} \log_2 \det \left(\mathbf{I} + \frac{P_{\mathrm{Tx}}}{\sigma_{\mathrm{n}}^2 N_{\mathrm{T}}} \mathbf{H}_k \mathbf{H}_k^{\mathrm{H}} \right)$$

Achievable Mutual Information (constrained by Standard)

$$I_{\mathrm{a}}(P_{\mathrm{Tx}}) = \max_{\mathbf{W} \in \mathcal{W}} \frac{\beta B}{K} \sum_{k=1}^{K} \log_2 \det \left(\mathbf{I} + \frac{\alpha P_{\mathrm{Tx}}}{\sigma_{\mathrm{n}}^2 N_{\mathrm{T}}} \mathbf{H}_k \mathbf{W} \mathbf{W}^{\mathrm{H}} \mathbf{H}_k^{\mathrm{H}} \right)$$

Throughput Losses

- **Channel State Information (CSI) Loss:**

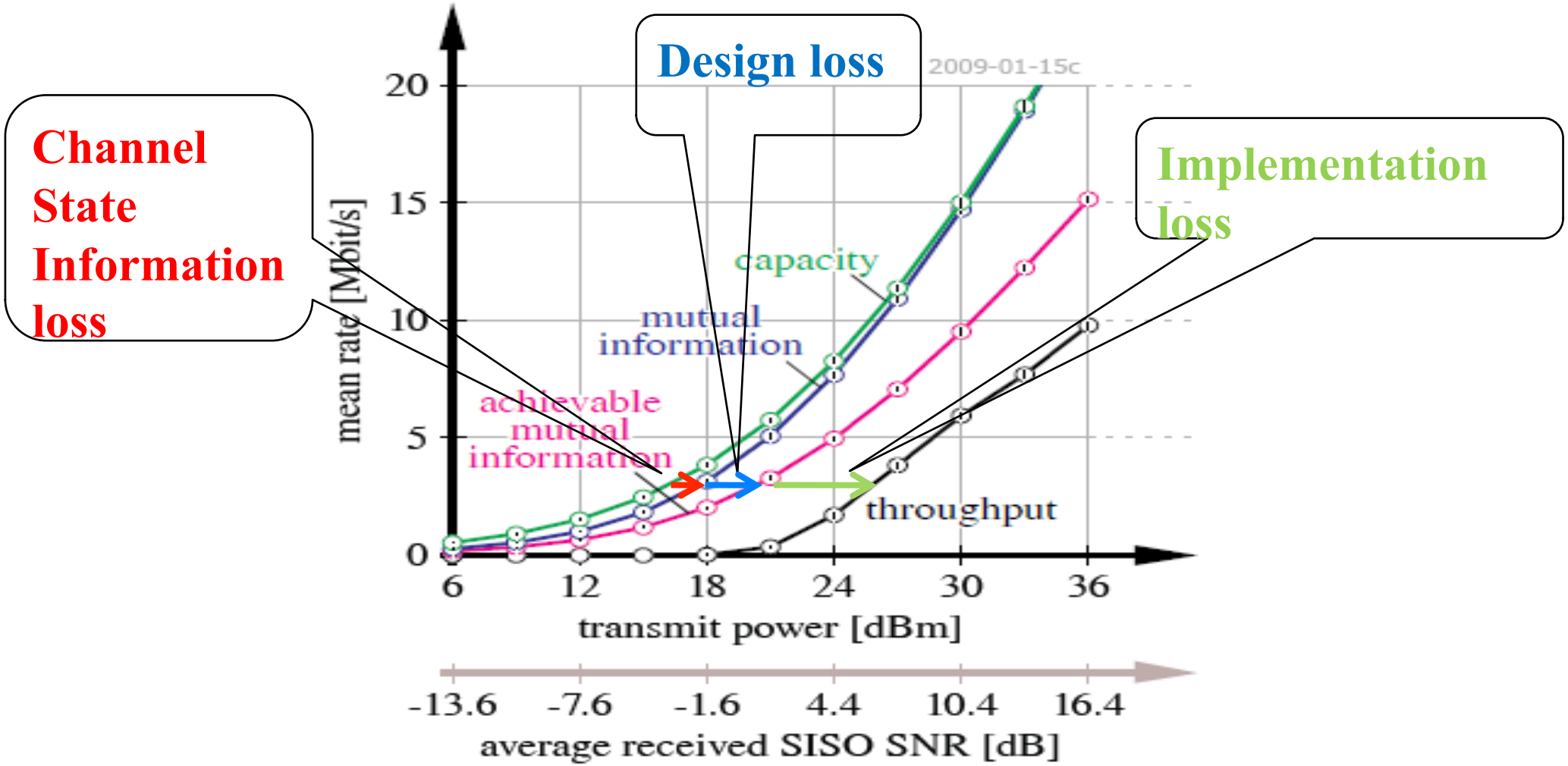
$$L_{\mathrm{CSI}}(P_{\mathrm{Tx}}) = C(P_{\mathrm{Tx}}) - I(P_{\mathrm{Tx}}); \quad L_{\mathrm{CSI}\%}(P_{\mathrm{Tx}}) = 100 \cdot \frac{C(P_{\mathrm{Tx}}) - I(P_{\mathrm{Tx}})}{C(P_{\mathrm{Tx}})}$$

- **Design Loss**

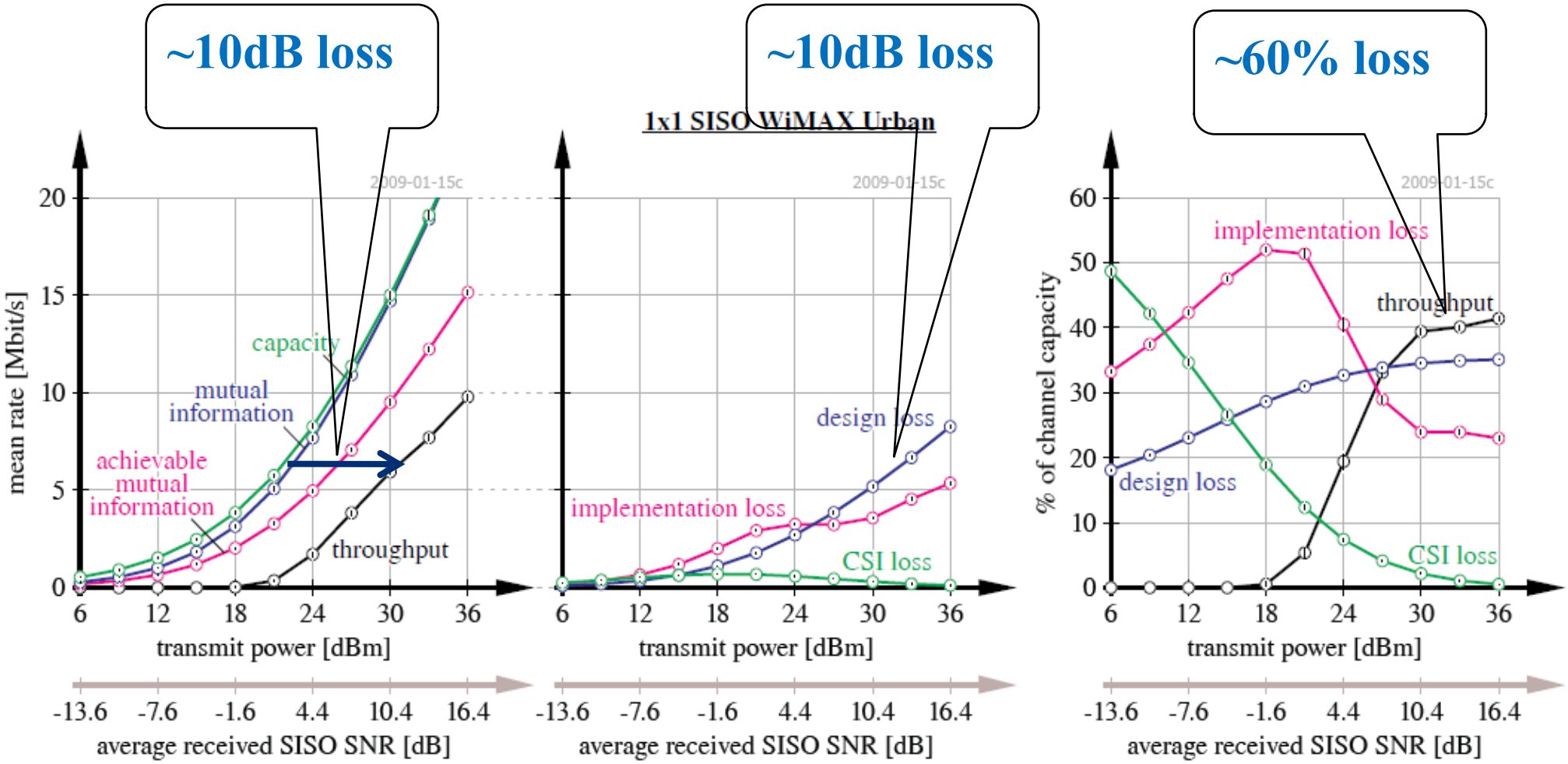
$$L_{\mathrm{d}}(P_{\mathrm{Tx}}) = I(P_{\mathrm{Tx}}) - I_{\mathrm{a}}(P_{\mathrm{Tx}}); \quad L_{\mathrm{d}\%}(P_{\mathrm{Tx}}) = 100 \cdot \frac{I(P_{\mathrm{Tx}}) - I_{\mathrm{a}}(P_{\mathrm{Tx}})}{C(P_{\mathrm{Tx}})}$$

- **Implementation Loss**

$$L_{\mathrm{i}}(P_{\mathrm{Tx}}) = I_{\mathrm{a}}(P_{\mathrm{Tx}}) - D_{\mathrm{m}}(P_{\mathrm{Tx}}); \quad L_{\mathrm{i}\%}(P_{\mathrm{Tx}}) = 100 \cdot \frac{I_{\mathrm{a}}(P_{\mathrm{Tx}}) - D_{\mathrm{m}}(P_{\mathrm{Tx}})}{C(P_{\mathrm{Tx}})}$$


Channel State Information loss
Design loss
Implementation loss
2009-01-15c
capacity
mutual information
achievable mutual information
throughput
mean rate [Mbit/s]
20
15
10
5
0
6
12
18
24
30
36
transmit power [dBm]
-13.6
-7.6
-1.6
4.4
10.4
16.4
average received SISO SNR [dB]

Performance Comparisons



Absolute Losses

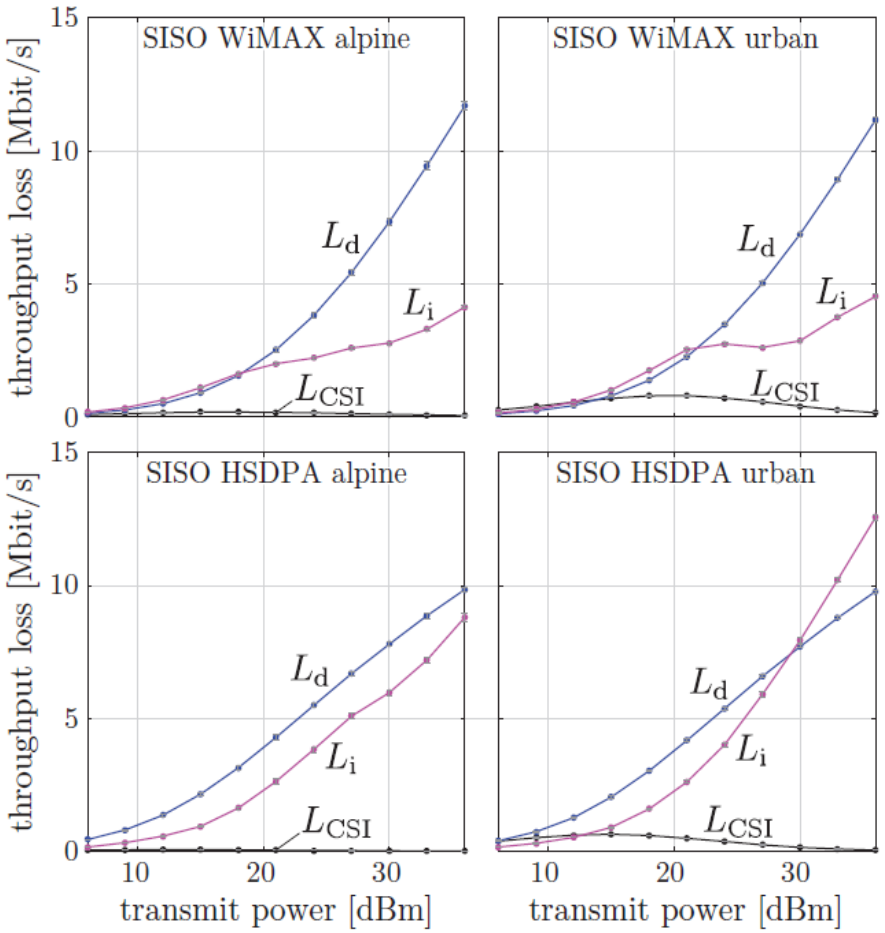


Fig. 2. Throughput losses of the SISO WiMAX and the SISO HSDPA systems in the alpine (ID "2008-09-23") and the urban environments (ID "2009-01-15c").

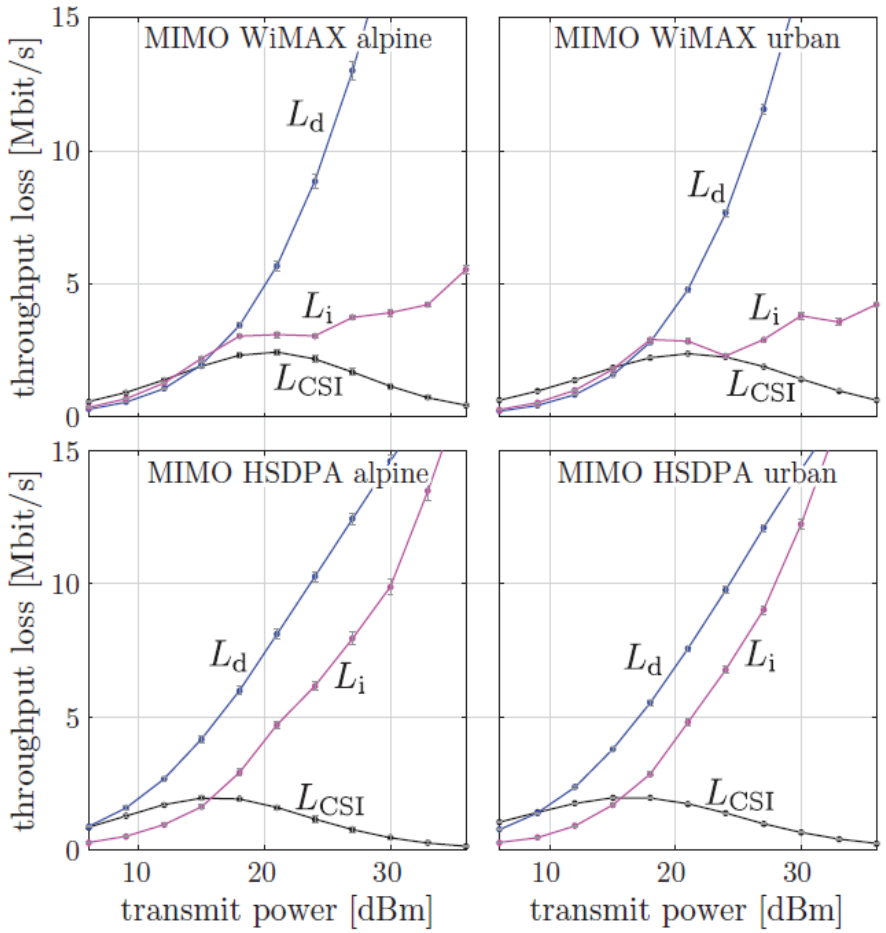
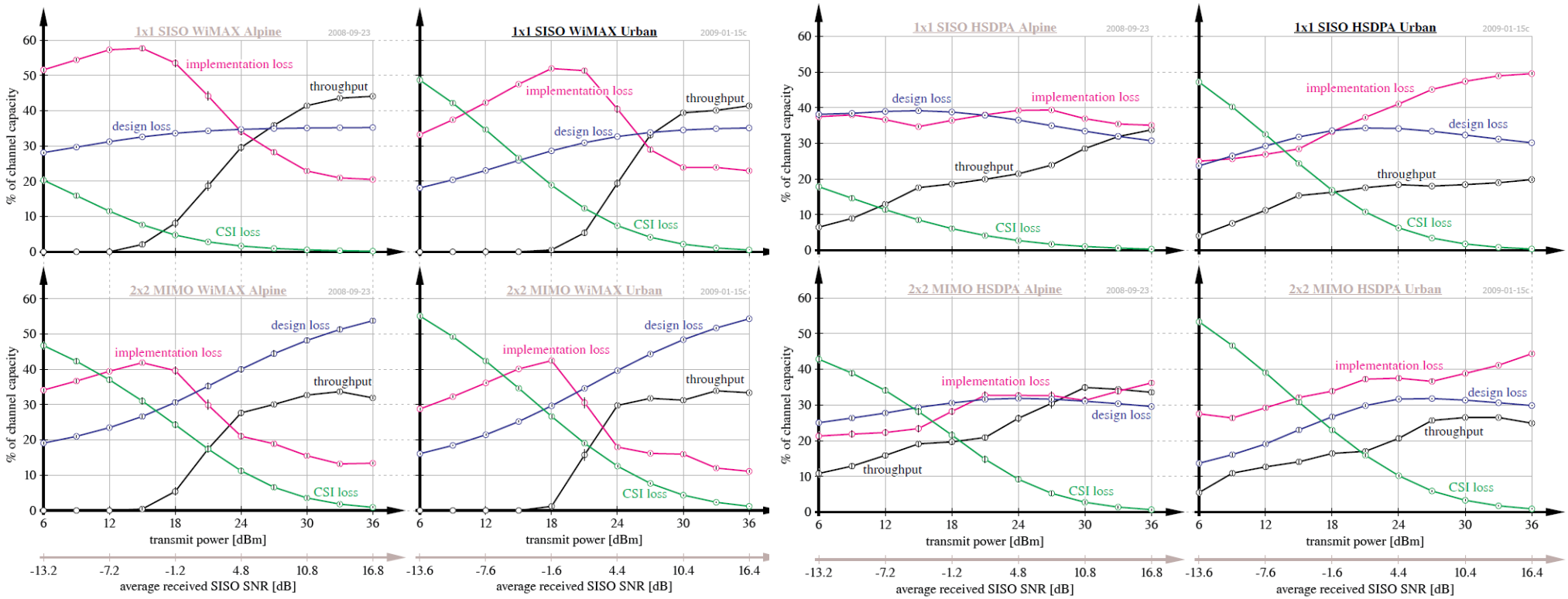


Fig. 3. Throughput losses of the MIMO WiMAX and the MIMO HSDPA systems in the alpine (ID "2008-09-23") and the urban environments (ID "2009-01-15c").

Relative Losses

- **WiMAX** **HSDPA**



Conclusion

- **WiMAX and HSDPA are ~10dB off from the Shannon Bound!**

  Less than half of the potential throughput is achieved.

- **Channel estimation loss**
  - **2-3dB channel estimator**
  - **6-9dB in HSDPA due to self-interference**
- **Coding loss**
  - **5dB convolutional codes (WiMAX)**
  - **2-3dB Turbo**
  - **1-2dB LDPC**
- **CQI (PCI) indicators need to be selected optimally**
  - **1-2dB loss depending on scenario**

Thank you for your attentio

http://www.nt.tuwien.ac.at/

Testbed References

[T1] Sebastian Caban, Christian Mehlführer, Robert Langwieser, Arpad L. Scholtz, Markus Rupp, "**Vienna MIMO Testbed**," in *EURASIP JASP Special Issue on Implementation Aspects and Testbeds for MIMO Systems,* Vol. 2006, Article ID 54868 (2006), http://publik.tuwien.ac.at/files/pub-et_10929.pdf.

[T2] Markus Rupp, Christian Mehlführer, Sebastian Caban, Robert Langwieser, Lukas W. Mayer, Arpad L. Scholtz, "**Testbeds and Rapid Prototyping in Wireless System Design**," in *EURASIP Newsletter,* 17 (2006), pp. 32-50, http://publik.tuwien.ac.at/files/pub-et_11232.pdf.

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