Measurement-Based Evaluation of the LTE MIMO Downlink at Different Antenna Configurations

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***Abstract*—Multi-antenna transmission modes are an integral feature of the 3GPP LTE downlink. While these modes are well defined in the standard there are no restrictions on the choice of transmit and receive antennas. In order to investigate the impact of the basestation antenna configuration on the LTE open loop downlink, a measurement campaign, comparing horizontally and vertically spaced antenna configurations for the two and four antenna case was performed whereas a considerable difference in performance depending on the antenna configuration is observed. Besides the evaluation in terms of LTE physical layer throughput the channel capacity and other measures have been calculated as upper bounds for the performance of a communication system. A comparison of the results for one, two and four transmit antennas shows that less than 50% of the channel capacity are reached and the higher the number of transmit antennas, the larger the gap between channel capacity and achievable throughput.**

I. Introduction

Different measurements and field tests such as [1], [2] have shown up that the performance of the LTE downlink depends on the antenna configuration whereas the best performing antenna configuration depends on the scenario, the received power and the transmission mode. In typical field tests measurements many different scenarios are performed whereas conditions such as the received power are given by the actual scenario. The measurement presented here is based on a different measurement methodology. In a single scenario all signals of interest are transmitted over a wide range of transmit power, allowing a more detailed evaluation of the impact of the transmit antenna configuration and the number of antennas on the performance of different transmission modes.

The LTE downlink transmission modes investigated in the presented measurements are *SISO* (mode 1), *Transmit Diversity* (mode 2) and *Open Loop Spatial Multiplexing* (mode 3). Mode 1 and 2 transmit a single data stream using 1 (SISO), 2 or 4 (transmit diversity) transmit antennas while mode 3 is capable of transmitting two spatial streams (layers[1]) over two transmit antennas or 2, 3 or 4 spatial streams when employing four transmit antennas. Using spatial multiplexing the number of receive antennas has to be at least the number of spatial streams. In the measurements presented here the number of transmit antennas equals the number of receive antennas in all configurations.

[1]The number of layers is often denoted as *transmission rank* or just *rank*

II. Measurement methodology and setup

A. Measurement setup

Measurements were taken in an urban scenario using a 4×4 MIMO testbed located at the Vienna Univesity of Technology in the city of Vienna, Austria. In this scenario a basestation located on a rooftop serves a single user located indoors. An overview of the measurement setup is given by Fig. 1.

System bandwidth	10 MHz, scheduled for a single user
Transmission modes	SISO, Transmit Diversity, Open Loop Spatial Multiplexing
Carrier frequency	2.5 GHz (λ =12 cm)
Transmit power	-13 . . . 35 dBm
Transmit antennas	4 x Kathrein 80010541 X pol
Transmit antenna spacings	1.5λ, 5.75λ, 10λ (horizontal) $\approx 11\lambda$ (vertical)
Transmit antenna polarizations	2×2: cross polarized & equally polarized 4×4: double cross polarized

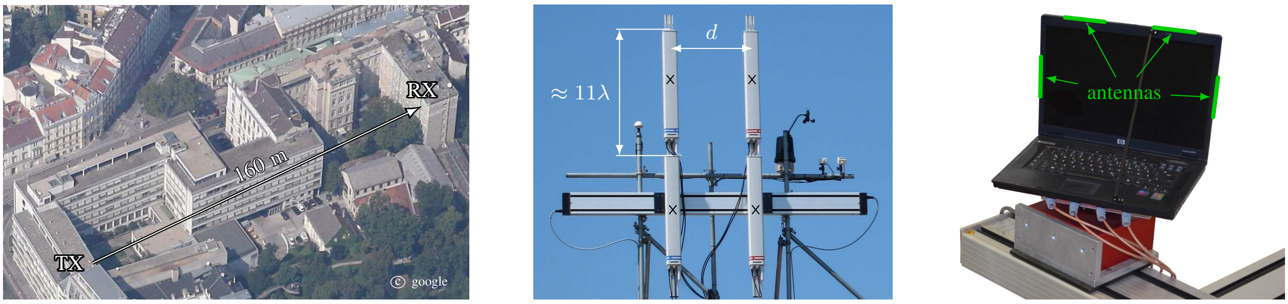
At the transmitter site two pairs of vertically mounted typical commercial cross polarized antennas that can be moved separately along a linear guide are utilized to implement both vertically stacked antennas and horizontally spaced antennas with arbitrary spacings. The four output channels of the transmitter can be mapped to four out of eight antennas. The receive antennas are two horizontally and two vertically polarized custom build patch-antennas mounted around the display of a laptop. The laptop is mounted on a $XY\Phi$ positioning table and can so be moved within an area of about $3\lambda\times3\lambda$ and rotated within a range of about $210°$.

B. Measurement methodology

The testbed [3] is capable of transmitting arbitrary signals and is not an implementation of a certain communications standard such as LTE. For the implementation of LTE the software based Vienna LTE Link Level Simulator [4], [5] is used. Subframes of all desired transmission modes and transmission parameters are pre-generated and systematically transmitted for every value of the transmit power, every implementation of every transmit antenna configuration and different receive antenna positions.

Measuring at just a single implementation of a transmit antenna configuration would not result in a fair comparison since different antenna elements at different locations are

ISBN 978-3-8007-3466-5



(a) (b) (c)

Fig. 1. (a) Urban outdoor to indoor scenario in the city of Vienna. (b) Transmitter: Two separately shiftable pairs of vertically stacked antennas allow for measurements at vertical and horizontal transmit antenna configurations. (c) Receiver: A laptop carrying the receive antennas can be moved along the X, Y and Φ axis in order to generate different channel realizations.

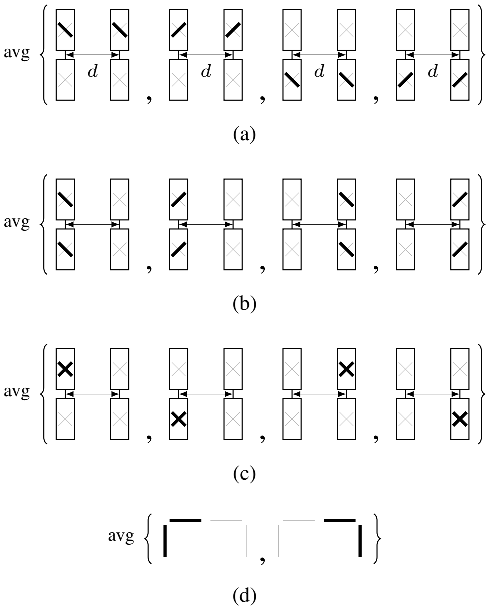


Fig. 2. 2×2 transmit antenna implementations: (a) horizontally spaced equally polarized antennas (b) vertically spaced equally polarized antennas and (c) cross polarized antennas. (d) For 2×2 measurements results are averaged over two different receive antenna configurations allowing a comparison with 4×4 measurements.

employed for different antenna configurations. For that reason measurements are repeated for every possible implementation of a transmit antenna configuration. Then as illustrated in Fig. 2 and Fig. 3 when averaging the results over all possible implementations the same antenna elements are used for every antenna configuration. For 1×1 measurements the results of all available antenna element measurements are averaged. Different channel realizations to average over are obtained by repeating all measurements for different $XY\Phi$ positions of the receive antennas. In order to compare various antenna configurations, 2×2 setups are averaged over two different receive antenna configurations and 1×1 setups are averaged over all four.

III. Evaluation

The LTE receiver provides for every subframe transmitted results for the LTE physical layer coded throughput

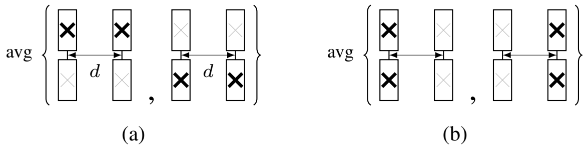


Fig. 3. 4×4 transmit antenna implementations: (a) horizontal and (b) vertical double cross polarized antennas.

$D_n\left(P_{TX}, \text{MCS}, \text{rank}\right)$, channel estimates $\mathbf{H}$ for every subcarrier as well as received signal power σ_x^2 and noise power σ_n^2. With these results the average LTE throughput can be calculated on the one hand and several standard independent measures [6] such as the channel capacity on the other hand.

A. LTE physical layer throughput

Assuming an LTE system choosing the best performing transmission rank[2] and modulation and coding scheme MCS for every channel realization n, the average LTE physical layer throughput over N channel realizations is calculated as

$$D\left(P_{TX}\right) = \frac{1}{N}\sum_{n=1}^{N} \max_{\text{MCS,rank}} D_n\left(P_{TX}, MCS, rank\right), \quad (1)$$

whereas $D_n\left(P_x, MCS, rank\right)$ is the measured throughput. In order to compare the impact of different antenna configurations in more detail for every transmission rank the throughput of a rank r transmission calculates as

$$D_r\left(P_{TX}\right) = \frac{1}{N}\sum_{n=1}^{N} \max_{\text{MCS}} D_n\left(P_{TX}, MCS, rank = r\right). \quad (2)$$

In Fig. 4 the measured LTE throughput for the 2×2 measurement is plotted. While the throughput for rank $= 1$ is quite independent of the transmit antenna configuration, there are rather large differences for a rank 2 transmission. The higher the antenna spacing, the better the performance whereas cross polarized antennas outperform all other configurations. Maximizing over the transmission rank at every

[2]In the MIMO case transmit diversity is used as rank $= 1$ transmission mode and Open Loop Spatial Multiplexing for rank > 1.

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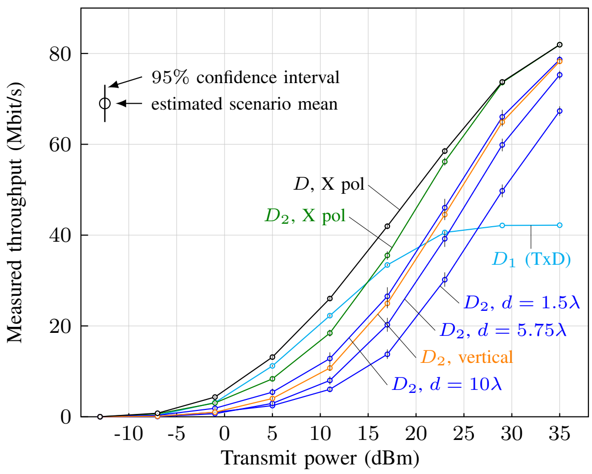

Fig. 4. Measured LTE physical layer throughput of a 2×2 system for different transmit antenna configurations separately for every transmission rank (D_r) and for cross polarized transmit antennas when maximizing over the transmission rank (D).

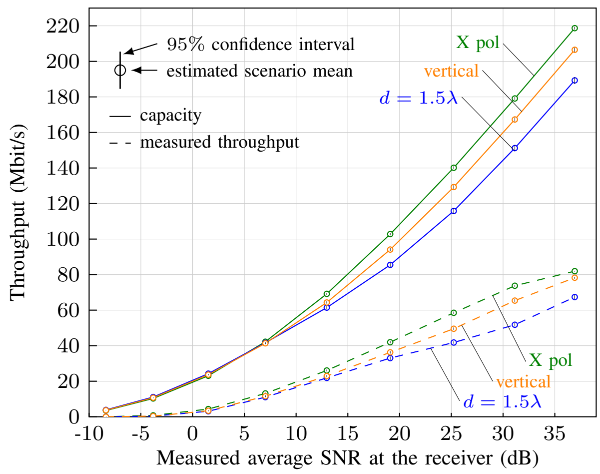

Fig. 6. Channel Capacity and LTE physical layer throughput for different 2×2 transmit antenna configurations. The results in terms of throughput and in terms of channel capacity are consistent.

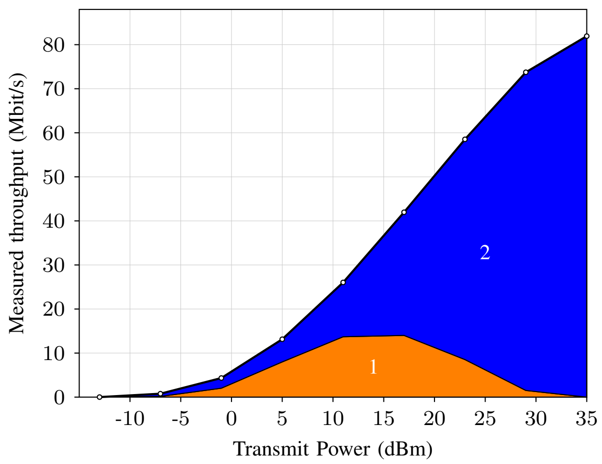

Fig. 5. Contribution of a rank r transmissions to the average throughput when choosing r as the best performing transmission rank for the 2×2 case using cross polarized antennas.

channel realization yields a curve that is close to the rank $= 1$ curve for small values of the average receive power and close to the rank $= 2$ curve for large power, while in between the throughput is higher than the maximum of both curves. This smooth transition from rank 1 to rank 2 over a wide range of transmit power is illustrated in Fig. 5.

B. Channel capacity

Using the channel estimates included in the output of the LTE receiver, the channel capacity [7] has been calculated as an upper bound for the throughput of a system where full channel state information is available at the transmitter and every subcarrier is precoded with the optimum precoder $\mathbf{R}_k$ calculated using the waterfilling algorithm.

For a system working on K subcarriers, a channel bandwidth B and N_T transmit antennas, the channel capacity $C(P_TX)$ as a function of the measured channels $\mathbf{H}_k$, the optimum precoders $\mathbf{R}_k$, the measured noise variance σ_n^2 and the transmit power P_x is given by:

$$C(P_{TX}) = \frac{B}{K}\sum_{k=1}^{K}\log_2 \det\left(\mathbf{I} + \frac{P_{TX}}{\sigma_n^2 N_T}\mathbf{H}_k\mathbf{R}_k\mathbf{H}_k^H\right) \qquad (3)$$

whereas the measured channels $\mathbf{H}_k$ were measured at the highest transmit power and the SNR was adjusted according to the other values of transmit powers in the measurement.

Due to the guard band of 1 MHz used in the $B = 10$ MHz LTE downlink, there are only channel measurements over a bandwidth of 9 MHz available. Thus the capacity is averaged over 9 MHz and extrapolated over the full bandwidth of 10 MHz.

C. Mutual information

If no channel and frequency specific precoding is performed the transmit power is equally spread over all subcarriers and antennas, the throughput is bounded by the mutual information:

$$I(P_{TX}) = \frac{B}{K}\sum_{k=1}^{K}\log_2 \det\left(\mathbf{I} + \frac{P_{TX}}{\sigma_n^2 N_T}\mathbf{H}_k\mathbf{H}_k^H\right). \qquad (4)$$

Consider the eigenvalues of $\mathbf{H}_k\mathbf{H}_k^H$ ordered in decreasing size from $\lambda_1 = \lambda_{\max}$ to λ_n. Defining $\tilde{\lambda_n}$ as the ratio of the n-th eigenvalue and the first eigenvalue

$$\tilde{\lambda_n} = 10\log_{10}\left(\frac{\lambda_n}{\lambda_1}\right), \qquad (5)$$

the evaluation of the 2×2 measurement at high SNR yields the results given by Table I.

TABLE I. Eigenvalues of the Measured 2×2 Channels

	$d = 1.5\lambda$	$d = 5.75\lambda$	$d = 10\lambda$	vertical	X polarized
$\tilde{\lambda}_2$	-37.9 dB	-30.9 dB	-26.9 dB	-27.3 dB	-19.7 dB

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These results are consistent with the results in terms of throughput in Fig. 4 and in terms of channel capacity in Fig. 6.

D. Achievable mutual information

Taking the constraints of a real communication system into account, a factor α reduces the mutual information to the achievable mutual information as an upper bound for the throughput a real communication system can achieve:

$$I_a(P_{TX}) = \alpha \frac{B}{K} \sum_{k=1}^{K} \log_2 \det \left(\mathbf{I} + \frac{P_{TX}}{\sigma_n^2 N_T} \mathbf{H}_k \mathbf{H}_k^H \right) \quad (6)$$

whereas for LTE α depends on following factors[3]:

- The *guard band* reduces the effective bandwidth.
- Using the normal *cyclic prefix* the effective symbol duration is reduced by $\frac{1}{15}$.
- Depending on the number of transmit antennas 4, 8 or 12 of 84 symbols per resource block are occupied by *reference symbols*.

For a 10 MHz LTE signal with a guard band of 1 MHz, it was found that $\alpha = 0.8$ for one transmit antenna, 0.76 for two transmit antennas and 0.72 for four transmit antennas.

An example showing the different measures is given by Fig. 7. At high SNR the measured LTE throughput is limited by the datarate of the modulation and coding scheme with the highest datarate while the other measures are standard independent and keep increasing for high SNRs. At low SNRs a quite similar behaviour can be observed. While the LTE throughput becomes zero below a certain SNR all the other measures decrease with decreasing SNR but do not become zero. A comparison of the channel capacity and the mutual information shows an increasing gain for decreasing SNRs due to the power allocation of the waterfilling algorithm.

E. Relative throughput

Finally the relative throughput can be definded as a measure for the efficiency of a real communication system as the ratio of the measured throughput to the channel capacity:

$$D_{\%}(P_{TX}) = 100 \cdot \frac{D(P_{TX})}{C(P_{TX})}. \quad (7)$$

F. Measured average SNR

In order to plot results in a more convenient way that allows for a comparison to simulations and other measurements, the measured average SNR for N channel realizations as a function of the transmit power P_{TX} is calculated as the ratio of the average of the measured received signal power σ_x^2 to the average of the measured noise power σ_n^2:

[3]In the measurements all resources that are normally reserved for control channels and synchronization were used for user data.

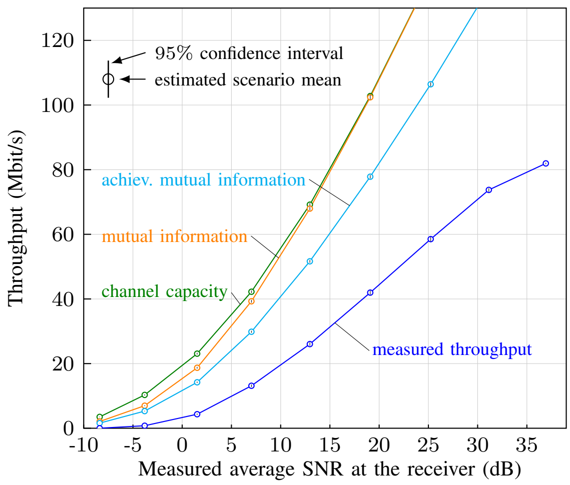

Fig. 7. Measured LTE throughput and different bounds of a 2 × 2 system using cross polarized transmit antennas.

$$\mathrm{SNR}(P_{TX}) = \frac{\sum_{i=1}^{N} \sigma_x^2(P_{TX}, i)}{\sum_{i=1}^{N} \sigma_n^2(P_{TX}, i)}. \quad (8)$$

IV. Measurement Results

Using two transmit antennas (Fig. 9a) the cross polarized configuration outperforms all the other configurations. The higher the antenna spacing, the better the performance of equally polarized antennas, whereas the vertical spacing of $\approx 11\lambda$ performs as good as the horizontal spacing of $d = 10\lambda$. At lower SNR regions where mostly on transmit diversity as best transmission mode is decided, the difference between different antenna configurations is negligible.

The results of the 4×4 measurements are plotted separately for every transmission rank in Fig. 8 and when maximizing over the transmission rank in Fig. 9b. The performance of transmit diversity is quite independent of the transmit antenna configuration. Different to the 2×2 case, the throughput of rank 2 transmissions is also quite the same for all measured antenna configuration. For rank $= 3$ and rank $= 4$ the performance increases the larger the spacing between the antennas becomes. As for 2×2 a vertical separation of $\approx 11\lambda$ performs quite the same as a horizontal spacing of 10λ, but only for rank 3. Transmitting over four layers the perfomance of the vertical stacked antennas worsens compared to the 10λ horizontal spaced antennas. The eigenvalues of the measured 4×4 channels given by Table II show the same behaviour.

TABLE II. Eigenvalues of the Measured 4 × 4 Channels

	$d = 1.5\lambda$	$d = 5.75\lambda$	$d = 10\lambda$	vertical
$\tilde{\lambda}_2$	−15.1 dB	−15.5 dB	−15.0 dB	−14.9 dB
$\tilde{\lambda}_3$	−41.8 dB	−34.6 dB	−30.1 dB	−30.7 dB
$\tilde{\lambda}_4$	−60.5 dB	−51.1 dB	−46.6 dB	−49.5 dB

In Fig. 10 a comparison of the results for different numbers of transmit antennas is given in terms of LTE physical layer throughput and in terms of relative throughput. For 2×2 and

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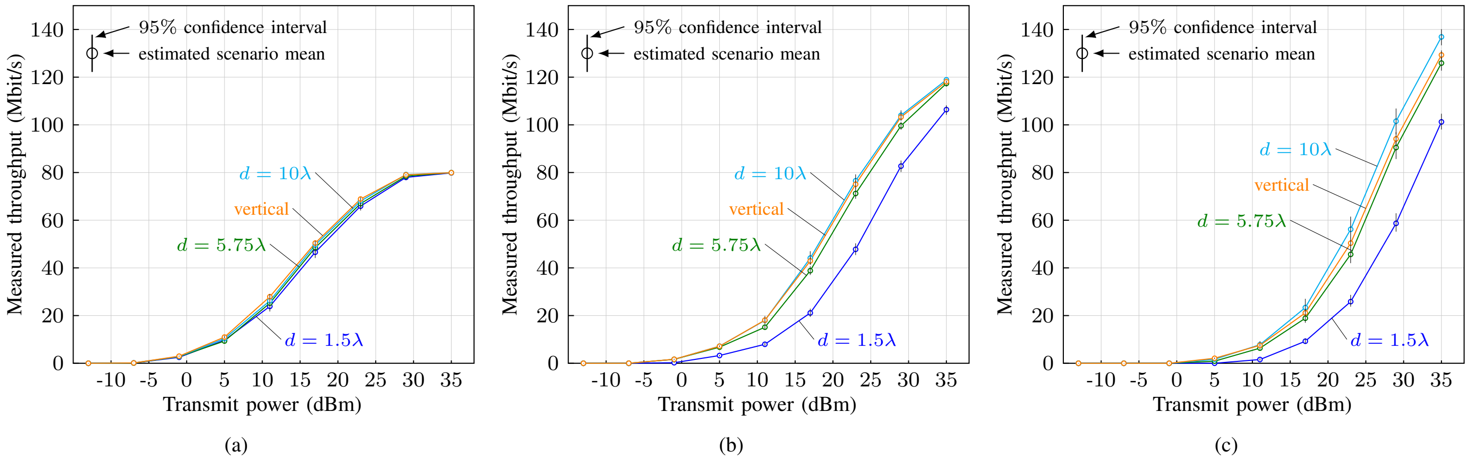


Fig. 8. Comparison of the measured LTE physical layer throughput of a 4×4 system for different transmit antenna configurations. The results are plotted separately for the (a) two, (b) three and (c) four layer case.

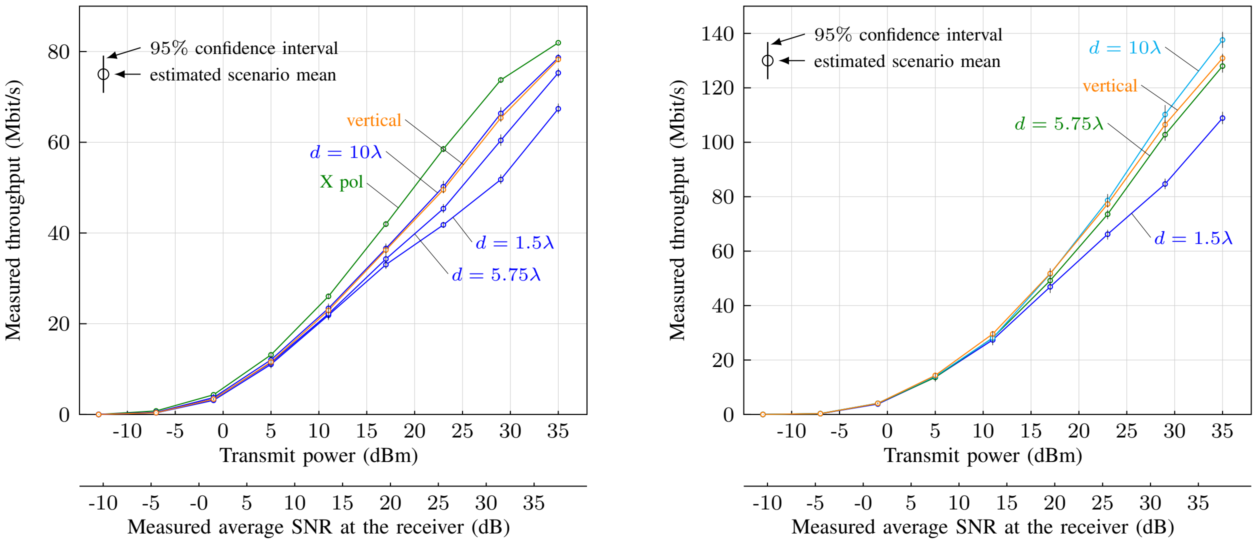


Fig. 9. LTE physical layer throughput measured at (a) different 2×2 antenna configurations where cross polarized antennas performed best and (b) different 4×4 antenna configurations where a horizontal spacing of 10λ performed best.

4×4 the respectively best performing antenna configuration is plotted. The higher the SNR, the higher the gain when using a larger number of transmit antennas. Even for rather low SNRs where mainly transmit diversity is used instead of spatial multiplexing, 2×2 and 4×4 systems perform at least as good as 1×1. The higher overhead for a higher number of transmit antennas causes a loss on the one hand when transmitting only a single spatial stream. On the other hand, the gain due to receive diversity is the higher, the higher the number of receive antennas.

The relative throughput in Fig. 10b increases with increasing SNR until a maximum is reached. The maximum is reached when the absolute throughput starts to saturate due to the limited number of MCSs. When using spatial multiplexing furthermore, the highest possible transmission rank is then used. The value of this maximum is the lower, the higher the number of transmit antennas. This is mainly caused by the higher overhead for a higher number of transmit antennas.

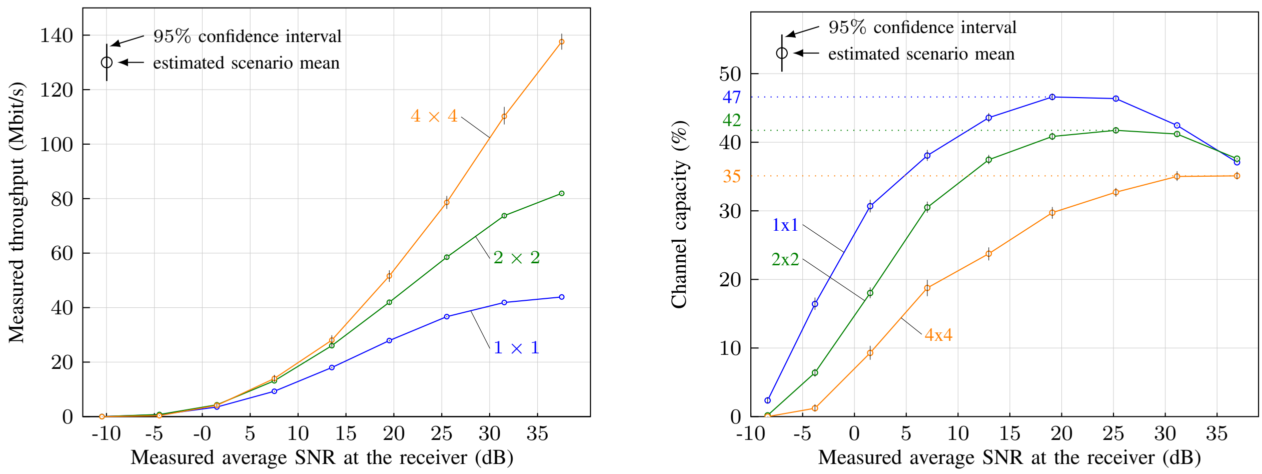
V. Conclusion

Spatial multiplexing is a proper technique utilized in the LTE downlink to increase the throughput. The higher the number of transmit antennas, the more can be benefit from this technique. A measurement was performed to show that the higher the horizontal separation of the basestation antennas, the better the performance of a 4×4 system whereas vertically stacked antennas perform quite as good. Furthermore cross polarized transmit antennas were shown to be the best performing configuration for 2×2 systems.

Acknowledgment

The authors would like to thank the LTE research group and in particular Prof. Christoph Mecklenbräuker and Sebastian Caban for continuous support. This work has been funded by the Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility, KATHREIN Werke KG, and A1

ISBN 978-3-8007-3466-5



(a) (b)

Fig. 10. Comparison of 1×1, 2×2 (cross polarized) and 4×4 (horizontal spacing of 10λ) in terms of (a) absolute throughput and (b) relative throughput.

Telekom Austria AG. The financial support by the Federal Ministry of Economy, Family and Youth and the National Foundation for Research, Technology and Development is gratefully acknowledged.

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