Measuring the Closed-Loop Throughput of 2x2 HSDPA over TX Power and TX Antenna Spacing

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Abstract. Mobile network operators demand small base station antennas and high physical layer throughputs. In the downlink, high physical layer throughputs can be achieved by exploiting transmit diversity. Given that the correlation between different propagation paths reduces the achievable throughput, it is commonly conjectured that the greater the transmit antenna spacing, the better the radio link performance. The open question is, how much does the throughput of a communication system actually change over antenna spacing?

We answer this question by closed-loop throughput measurements at 2.5 GHz for standard compliant 2×2 HSDPA in a realistic, urban, outdoor scenario. The results are presented in terms of physical layer throughput over TX antenna spacing and TX power. We arrive at the somehow surprising conclusion that, for typical TX power values and typical antenna spacings, the throughput remains approximately independent with respect to the antenna spacing.

Keywords: Antenna diversity, Antenna spacing, Measurement, MIMO systems, Radio communications, HSDPA.

1 Introduction

The High-Speed Downlink Packet Access (HSDPA) mode [1] was introduced in Release 5 of the Universal Mobile Telecommunications System (UMTS) to provide high data rates to mobile users. This is achieved by employing techniques like fast link adaptation, fast Hybrid Automatic Repeat reQuest (HARQ), and fast scheduling. Multiple Input Multiple Output (MIMO) HSDPA was standardized in Release 7 of UMTS and is capable of increasing the maximum downlink data rate by spatially multiplexing two independently coded and modulated data streams. Additionally, channel-adaptive spatial precoding is implemented at the base station. The standard defines a set of precoding vectors and one of them is chosen based on a precoding control indicator feedback obtained from the user

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equipment. Two different MIMO HSDPA modes are defined: the Transmit Antenna Array (TxAA) that utilizes two antennas to transmit a single stream, and the Double Transmit Antenna Array (D-TxAA) in which one or two streams (whichever leads to a higher throughput) are transmitted using two antennas. For comparison purposes, we defined additionally a two stream mode in which always two streams are transmitted.

A few experimental evaluations of HSDPA have been reported in the literature. For example, in [2] the throughput performance of a SISO HSDPA system is simulated based on so-called drive test measurements. Throughput measurement results of a SISO HSDPA system are presented in [3]. Finally, a non standard compliant MIMO HSDPA system was measured in [4]. However, apart from results published by the authors [5–7], we are not aware of publications showing the actual closed-loop throughput of a standard compliant MIMO HSDPA link.

The effects of antenna spacing at the transmitter and the receiver sides have been studied for a long time. First measurement campaigns carried out in outdoor scenarios date from the seventies (e.g. [8]). In these measurements, the **correlation coefficient** of the incoming signals with respect to antenna spacing was investigated. More recent measurements investigated this effect in indoor-only scenarios (e.g. [9]), in outdoor-to-indoor scenarios (e.g. [10]), and in outdoor-only scenarios (e.g. [11]).

The impact of antenna spacing on **channel capacity** has been measured intensively in a variety of scenarios and conditions, including indoor scenarios [12, 13], outdoor scenarios [12, 14, 15], reverberation chambers [16], and using virtual antenna arrays [17]. These measurement results were complemented with theoretical analyses (see [18–21] and references therein).

The **bit error ratio (BER)** has also been used as a metric for the evaluation of the performance of wireless systems with respect to the antenna spacing. In the literature, theoretic studies have been reported [22, 23]. Additionally, the influence of the antenna spacing on the BER has been evaluated in indoor [24, 25] and outdoor [26, 27] scenarios.

Recently, the influence of antenna spacing on the **throughput** of an OFDM transmission was studied in [28] by using sounded channel coefficients in a simulation. Similarly, [29] investigates the throughput difference between equally and cross polarized TX antennas. Remarkably, apart from [26, 28], all above cited references do not employ base station antennas similar to those currently in use in mobile cellular networks. Furthermore, except [28], none of the references found relates TX antenna spacing to the physical layer throughput of a standard compliant MIMO mobile communication system such as 2×2 MIMO HSDPA in our case.

2 Experimental Set-Up

The goal of the experimental set-up described below is to examine the impact of base station antenna spacing and polarization on the physical layer throughput

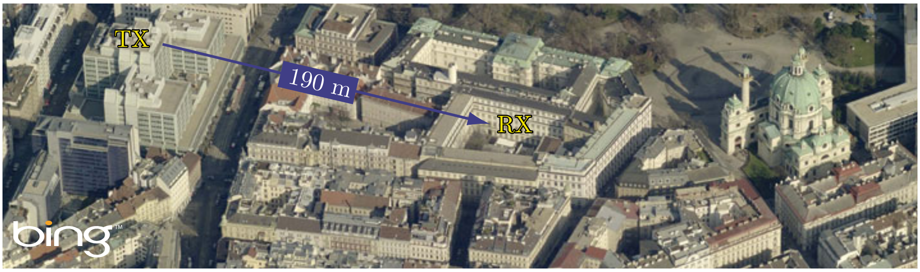

Fig. 1. Scenario overview [30]

of a standard compliant 2×2 MIMO HSDPA downlink transmission [1] under the following premises:

An Urban Outdoor Environment. We consider a realistic, non-line-of-sight scenario in the inner city of Vienna, Austria (see Figure 1). The TX antennas are placed on the roof of a tall building right adjacent to existing base station antennas of mobile phone operators (see Figure 2), making the measurement results obtained very realistic and representative for a mobile communication system. The RX antennas are placed in a small office (see Figure 3) at a distance of approximately 190 m (see Figure 1). The estimated root mean square delay spread for this rich scattering non-line-of-sight scenario is 0.5 µs (=1.9 HSDPA chip durations).

Closed-Loop Testbed Measurements. We employ closed-loop quasi-realtime testbed measurements as the hardware and experience required is readily available [5–7, 24, 31–33]. In our measurement approach, all possible transmitted data is generated off-line in MATLAB, but only the required data is then transmitted over a wireless channel which is altered by moving the receive antennas. The feedback calculation —mandatory for closed-loop HSDPA— is instantly calculated in MATLAB in approximately 40 ms (less than the channel coherence time). The received data itself is not evaluated in real-time but off-line using a cluster of PCs. Results for the scenario measured are automatically obtained using the same program that has already controlled the complete measurement procedure and documentation.

Flat Panel Antennas at the Base Station. At the base station, we employ two KATHREIN 800 10629 [34] 2X-pol panel antennas with a half-power beam width of 80°/7.5° and a total down tilt of 16° (= 10° mechanical + 6° electrical, see Figure 2). Each 2X-pol antenna consists of two cross-polarized antennas spaced by 0.6 λ (λ=12 cm at 2.5 GHz). Only two of the eight possible antenna elements are excited at the same time to obtain a two-element base station antenna with a variable element spacing from 0.6 λ to 7.7 λ for equal polarization, and 0 λ for cross polarization. Using two ordinary X-pol antennas instead of two 2X-pol antennas would have only allowed us to measure down to an element spacing of 1.3 λ, rather than 0.6 λ.

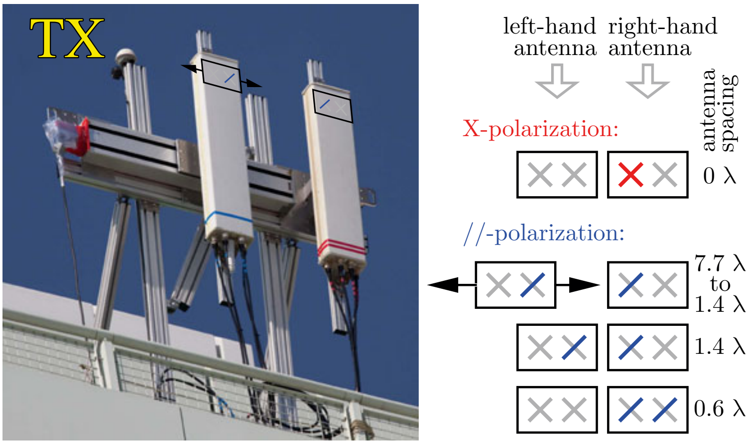

Fig. 2. A base station antenna consisting of a moveable 2X-pol antenna (left-hand) and a fixed 2X-pol antenna (right-hand). In total, only two antenna elements are excited at the same time.

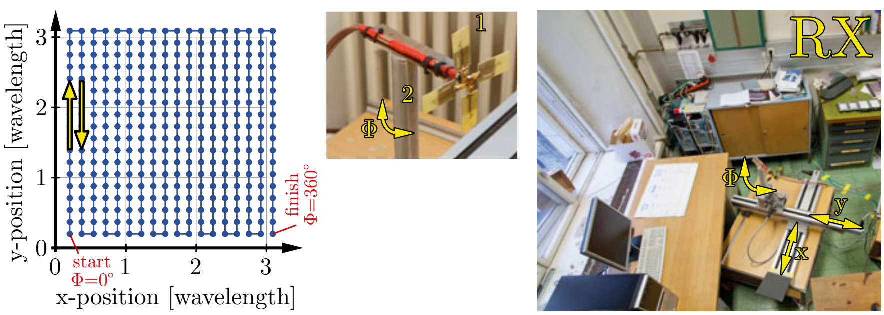

Fig. 3. The receiver employing two (1,2) moveable (x,y) and rotatable (Φ) printed monopole antennas. The other two printed monopole antennas shown are not used.

Two Printed Monopole Antennas at the Mobile Phone. At the receiver site, we utilize two realistic printed monopole antennas [35] that can be integrated into a mobile handset or a laptop computer. We employ differently polarized antennas to obtain robust and close to reality measurement results. As shown in Figure 3, we measure different receive antenna positions (x,y) in an area of $3\,\lambda \times 3\,\lambda$ to average over small scale fading and to avoid large scale fading effects. Because the antennas point into different directions, they experience a different average path loss. To average out this effect, we rotate the antennas (Φ) during the measurement.

A Standard-Compliant 2×2 MIMO HSDPA Transmission. We transmit standard compliant HSDPA data frames [1], including the pilot structure

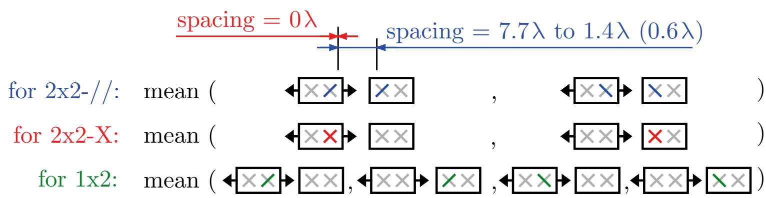

Fig. 4. Ensuring a fair comparison between 2×2 HSDPA with X-polarization, 2×2 HSDPA with //-polarization, and 1×2 HSDPA

[31, Chapter 3]. Three different HSDPA modes, either with equally (//) and cross-polarized (X) transmit antennas have been considered. In addition, a 1×2 SIMO mode has been also considered as a reference. In total, seven modes were measured:

- **One stream mode = TxAA** (1// and 1X). This is the so-called closed-loop Transmit Antenna Array (TxAA) mode with transmit diversity that uses strongly quantized precoding at the transmitter to increase the signal to interference and noise ratio (SINR) at the user equipment [31, pp. 48].
- **One-or-two stream mode = D-TxAA** (1or2// and 1or2X). This is the so-called Double TxAA mode (D-TxAA) that is downward compatible with TxAA. This mode equals TxAA when the SINR at the user equipment is low. At larger SINRs, D-TxAA switches to dual stream mode and transmits two independently coded HSDPA data streams. Thus, in TxAA, a single stream is always transmitted and in D-TxAA, either single-stream or double-stream is chosen [31, pp. 48] depending on which one leads to a higher physical layer throughput [36].
- **Two stream mode** (2// and 2X). For analysis purposes, we also implemented a two stream mode —non existent in the standard— that behaves like D-TxAA, but forces the transmitter to always use two streams, regardless of the SINR estimated at the receiver.
- **SIMO HSPDA** (1×2 SIMO). We measure 1×2 SIMO HSPDA as a reference and concomitant observations to enhance the precision of the 2×2 results measured over antenna spacing.

See [7] for a description of the procedure we use to measure in quasi real-time the closed-loop throughput of HSDPA by transmitting four frames: a "previous frame", a "data frame", and two possibly required retransmissions. More details about the algorithms used in the implementation can be found in [5]. Particularly, the channel estimation algorithm is described in detail in [37].

3 Inferring the Mean Scenario Throughput

When comparing the throughput of a "//-polarized transmission between 1.4 λ and 7.7 λ" to an "X-polarized transmission at 0 λ" as shown in Figure 2, the main problem is that these transmissions use different antenna elements, thus experiencing a greatly different (up to 4 dB) average path loss. This problem can be overcome by averaging the throughput measured at different antenna elements as shown in Figure 4. In other words, to measure, for example, the throughput of the 2×2-TxAA-// mode, we average two measurements, one exciting both /-elements, the other one exciting both \-elements. A similar procedure is used to measure at 0.6 λ.

We use well known statistical techniques explained in e.g. [38–40] to infer the mean throughput performance of the urban scenario as described below (*the technical terms are given in italics in brackets*):

1) We measure the seven HSDPA modes to be compared (*grouping, comparison*) in random order (*randomization*) immediately after each other over the same channels (*blocking*) equally often (*balancing*).
2) We measure all above at 11 different transmit power levels (the abscissas in Figure 5.a, Figure 7.a, and Figure 8.a (*one-factor-at-a-time experiment*).
3) We measure all above at 12 different transmit antenna spacings (see Figure 2) when //-polarized TX antennas are used (see Figure 5.b, Figure 6, and Figure 8.b) (*11×12 full factorial design*). When X-polarization is employed, the antenna spacing is 0 λ, therefore the results are plot as dots on the ordinate (see Figure 7.b, and Figure 8.b).
4) We measure all above at 324 different receive antenna positions (see Figure 3) (*systematic sampling*).
5) We evaluate all measured throughputs off-line and average them (best estimator for the mean having no other knowledge, *plug-in principle*) over the RX antenna positions to obtain the mean scenario throughput (the ordinates in Figure 5, Figure 6, Figure 7, and Figure 8).
6) We use the correlation between the 2×2 throughput values and the 1×2 throughput values (*concomitant observations*) to enhance the precision of the 2×2 results measured over antenna spacing[1].
7) Finally, we calculate the 99% confidence intervals for the mean (the vertical lines in Figure 5, Figure 6, Figure 7, and Figure 8) to gauge the precision of the results shown (*BC_a bootstrap algorithm*).

4 Results Obtained

The results obtained are shown in the nine graphs plotted in Figure 5, Figure 6, Figure 7, and Figure 8.

Figure 5.a shows the mean scenario throughput over transmit power for the three HSDPA modes measured with //-polarized transmit antennas. We observe that transmitting one stream (1//) works as well as transmitting one or

[1] Looking at the 12 transmit antenna spacings measured, the 2×2 and 1×2 HSDPA throughputs are correlated (correlation coefficient 99%-confidence-interval=[0.87, 0.98], linear regression coefficient 99%-confidence-interval=[0.79, 1.24]) whilst the 1×2 throughputs should not change over antenna *spacing* but do change over antenna *position*.

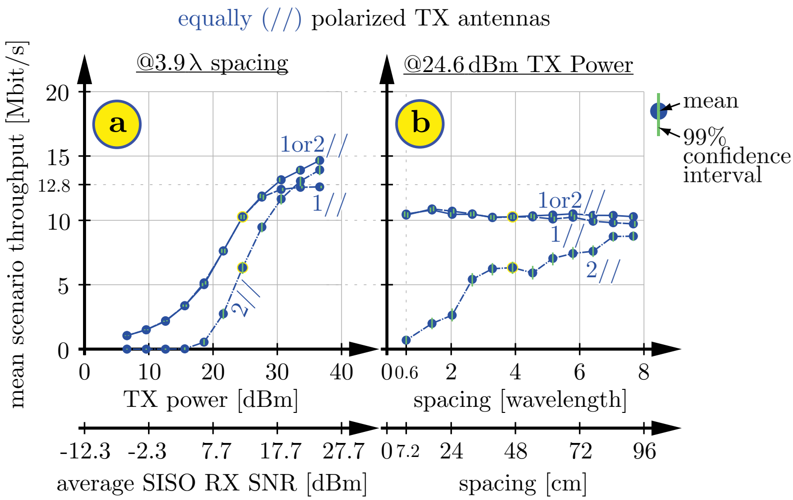

Fig. 5. Throughput of 2×2 HSDPA with 1 stream (=TxAA), 2 streams, and 1or2 streams (=D-TxAA) for equally (//) polarized transmit antennas

two streams (1or2//). Only at transmit power levels exceeding 27.6 dBm does transmitting one or two streams (1or2//) become advantageous because the 1// stream mode saturates at its theoretical maximum of 12.8 Mbit/s. Figure 5.a also shows how the transmission of two streams (2//) contributes to the high throughput achieved at high SINR values.

For antenna spacings greater than 5 λ, it can be seen in Figure 5.b that the 1or2// stream mode works slightly better than the 1// stream mode. This is because we have observed that the 2// stream mode works better than the 1// stream mode at some RX antenna positions.

Remarkably, the performance of the 2// stream mode is highly dependent on the TX antenna element spacing (see Figure 6.b). While the poor performance of the 2// stream mode at low antenna spacings is compensated by the excellent performance of the 1// stream mode (see Figure 6.a), the 2// stream mode outperforms the 1// stream mode at high transmit power values. The performance of the 1or2// stream mode is plotted in Figure 6.c, showing that the best performance is obtained when both 1// and 2// stream modes are combined.

Figure 7.a presents, over TX power, the three HSDPA modes measured with X-polarized elements at the transmitter. In contrast to //-polarization, the 1or2X mode is already better than the 1X mode at transmit power levels exceeding 13 dBm. As for X-polarization the active elements are always spaced by 0 λ, only dots on the ordinate are plot in Figure 7.b.

Because the results for equal and cross polarization are obtained by measuring at the same antenna elements (see Figure 4) we are able to directly compare the results shown in Figure 5 and Figure 7 in Figure 8.

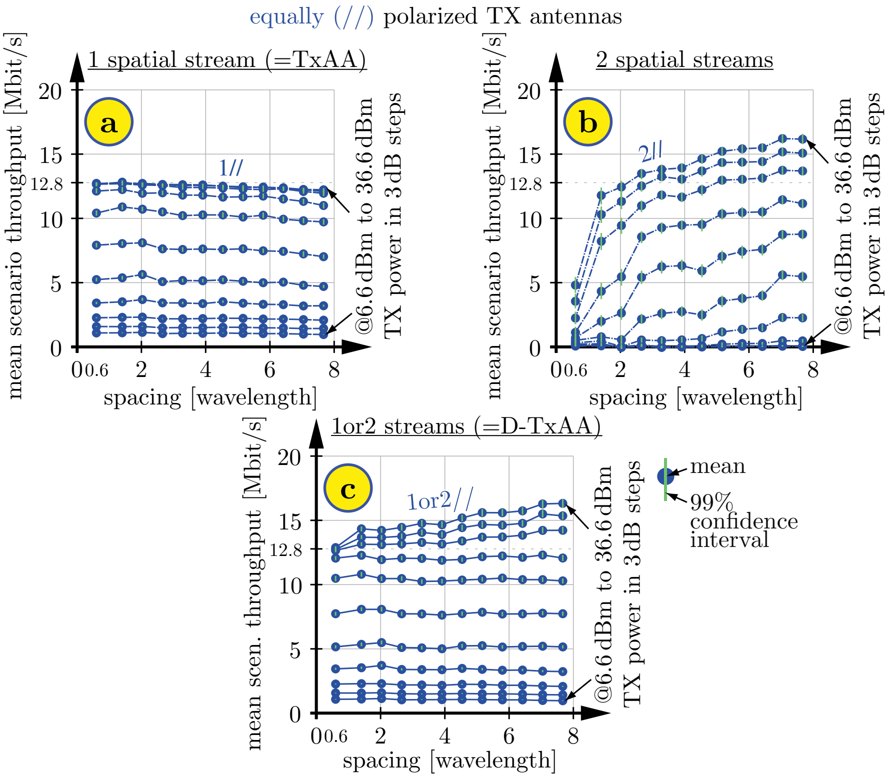

Fig. 6. Throughput of 2×2 HSDPA with 1 stream (=TxAA), 2 streams, and 1or2 streams (=D-TxAA) for equally (//) polarized transmit antennas

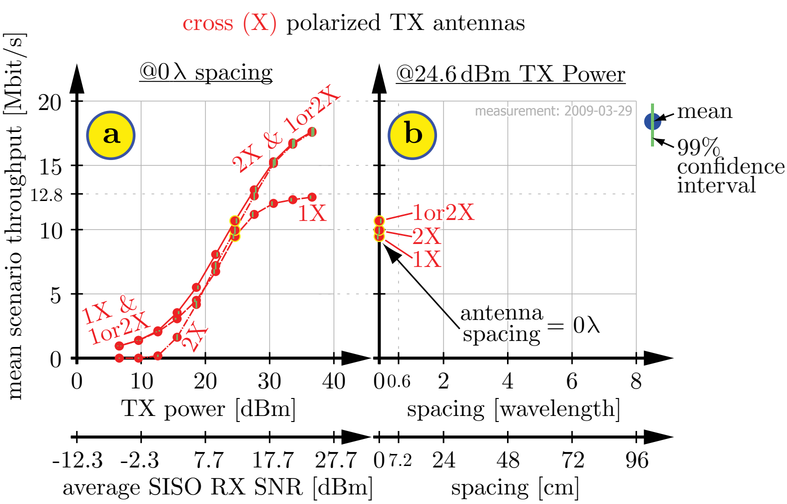

Fig. 7. Throughput of 2×2 HSDPA with 1 stream (=TxAA), 2 streams, and 1or2 streams (=D-TxAA) for cross (X) polarized transmit antennas

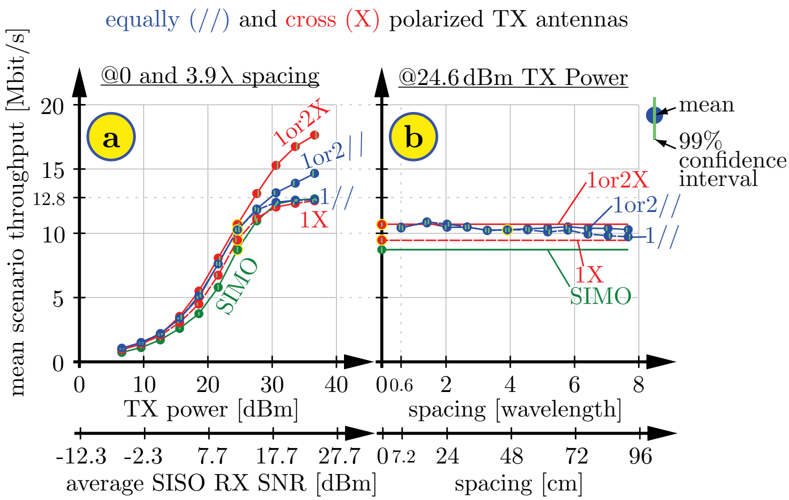

Fig. 8. Throughput of 2×2 HSDPA with 1 stream (=TxAA), 2 streams, and 1or2 streams (=D-TxAA) for equally (//) and cross (X) polarized transmit antennas

5 Conclusions

In this paper, the influence of TX antenna spacing and polarization on the closed-loop throughput of 2×2 MIMO HSDPA is investigated by testbed measurements. The measurement campaign was carried out in a realistic, urban, outdoor scenario in the inner city of Vienna with cross-polarized antennas at the receiver.

The results show that the 1or2X mode (D-TxAA with cross polarization) provides the highest physical layer throughput. On the contrary, polarization is not so important when only one spatial stream is allowed. Indeed, as shown in Figure 8, the performance of the 1// mode (TxAA with equal polarization) and the 1X mode (TxAA with cross polarization) is almost the same.

It is commonly conjectured that the throughput increases with the TX antenna spacing since separating the TX antennas provides higher spatial diversity due to lower correlation. However, the measurement results presented in this paper show that the throughput hardly depends on the antenna separation (see Figure 6.a, and Figure 6.c). Moreover, in some situations the throughput may even decrease with respect to antenna separation (see Figure 6.a). Only when the transmit power is relatively high (more than 27.6 dBm) and/or the 2// stream mode is used, the throughput clearly increases with respect to the antenna spacing (see Figure 6.b and Figure 6.c). However, for typical TX power values and typical antenna spacings, the throughput remains approximately independent of the antenna spacing.

Finally, it is very important to emphasize the influence of the antenna polarization on the physical layer throughput. The 2X and the 1or2X stream modes always outperform the 1or2// stream mode. Thus, more spatial diversity is obtained from using different polarizations rather than from using larger antenna spacings.

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References

1. 3GPP. Tech. spec. group radio access network, physical layer procedures (FDD) (Tech. Spec. 25.214 V7.7.0) (2007)
2. Landre, J.B., Saadani, A.: HSDPA 14.4 Mbps mobiles - realistic throughputs evaluation. In: Proc. of VTC 2008, Spring, pp. 2086–2090 (2008), doi:10.1109/VETECS.2008.468
3. Holma, H., Reunanen, J.: 3GPP release 5 HSDPA measurements. In: Proc. PIMRC 2006 (2006), doi:10.1109/PIMRC.2006.254116
4. Riback, M., Grant, S., Jongren, G., Tynderfeldt, T., Cairns, D., Fulghum, T.: MIMO-HSPA testbed performance measurements. In: Proc. PIMRC 2007 (2007), doi:10.1109/PIMRC.2007.4394434
5. Mehlfühurer, C., Caban, S., Rupp, M.: MIMO HSDPA throughput measurement results in an urban scenario. In: Proc. 70th IEEE Vehicular Technology Conference (VTC 2009-Fall), Anchorage, AK, USA (2009), doi: 10.1109/VETECF.2009.5378994, http://publik.tuwien. ac.at/files/PubDat_176321.pdf
6. García-Naya, J.A., Mehlführer, C., Caban, S., Rupp, M., Castedo, L.: Throughput-based antenna selection measurements. In: Proc. 70th IEEE Vehicular Technology Conference (VTC2009-Fall), Anchorage, AK, USA (2009), doi:10.1109/VETECF.2009.5378992, http://publik.tuwien.ac.at/files/PubDat_176573.pdf
7. Caban, S., Mehlführer, C., Lechner, G., Rupp, M.: Testbedding MIMO HSDPA and WiMAX. In: Proc. 70th IEEE Vehicular Technology Conference (VTC2009-Fall), Anchorage, AK, USA (2009), doi:10.1109/VETECF.2009.5378995, http://publik.tuwien.ac.at/files/PubDat_176574.pdf
8. Lee, W.: Effects on correlation between two mobile radio base-station antennas. IEEE Transactions on Communications 21(11), 1214–1224 (1973)
9. Kivinen, J., Zhao, X., Vainikainen, P.: Empirical characterization of wideband indoor radio channel at 5.3 GHz. IEEE Transactions on Antennas and Propagation 49(8), 1192–1203 (2001), doi:10.1109/8.943314

10. Medbo, J., Harrysson, F., Asplund, H., Berger, J.E.: Measurements and analysis of a MIMO macrocell outdoor-indoor scenario at 1947 MHz. In: Proc. of VTC 2004 Spring, vol. 1, pp. 261–265 (2004)
11. Zhao, X., Kivinen, J., Vainikainen, P., Skog, K.: Propagation characteristics for wideband outdoor mobile communications at 5.3 GHz. IEEE Journal on Selected Areas in Communications 20(3), 507–514 (2002), doi:10.1109/49.995509
12. Jungnickel, V., Pohl, V., von Helmolt, C.: Capacity of MIMO systems with closely spaced antennas. IEEE Communications Letters 7(8), 361–363 (2003), doi:10.1109/LCOMM.2003.815644
13. Intarapanich, A., Kae, P., Davies, R., Sesay, A., McRory, J.: Spatial correlation measurements for broadband MIMO wireless channels. In: Proc. of VTC 2004 Fall, vol. 1, pp. 52–56 (2004), doi:10.1109/VETECF.2004.1399919
14. Skentos, N., Kanatas, A., Pantos, G., Constantinou, P.: Capacity results from short range fixed MIMO measurements at 5.2 GHz in urban propagation environment. In: Proc. of ICC 2004, vol. 5, pp. 3020–3024 (2004), doi:10.1109/ICC.2004.1313086
15. Chizhik, D., Ling, J., Wolniansky, P., Valenzuela, R., Costa, N., Huber, K.: Multiple-input-multiple-output measurements and modeling in Manhattan. IEEE Journal on Selected Areas in Communication 21(3), 321–331 (2003), doi:10.1109/JSAC.2003.809457
16. Kildal, P.S., Rosengren, K.: Correlation and capacity of MIMO systems and mutual coupling, radiation efficiency, and diversity gain of their antennas: simulations and measurements in a reverberation chamber. IEEE Communications Magazine 42(12), 104–112 (2004), doi:10.1109/MCOM.2004.1367562
17. Medbo, J., Riback, M., Berg, J.E.: Validation of 3GPP spatial channel model including WINNER wideband extension using measurements. In: Proc. of VTC 2006 Fall, pp. 1–5 (2006), doi:10.1109/VTCF.2006.36
18. Chizhik, D., Rashid-Farrokhi, F., Ling, J., Lozano, A.: Effect of antenna separation on the capacity of BLAST in correlated channels. IEEE Communications Letters 4(11), 337–339 (2000), doi:10.1109/4234.892194
19. Shiu, D.S., Foschini, G., Gans, M., Kahn, J.: Fading correlation and its e ect on the capacity of multielement antenna systems. IEEE Transactions on Communications 48(3), 502–513 (2000), doi:10.1109/26.837052
20. Thushara, D., Rodney, A., Jaunty, T.: On capacity of multi-antenna wireless channels: Effects of antenna separation and spatial correlation. In: 3rd Australian Communications Theory Workshop (AusCTW) (2002)
21. Waldschmidt, C., Kuhnert, C., Schulteis, S., Wiesbeck, W.: Analysis of compact arrays for MIMO based on a complete RF system model. In: IEEE Topical Conference on Wireless Communication Technology, pp. 286–287 (2003), doi:10.1109/WCT.2003.1321527
22. Luo, J., Zeidler, J., McLaughlin, S.: Performance analysis of compact antenna arrays with MRC in correlated nakagami fading channels. IEEE Transactions on Vehicular Technology 50(1), 267–277 (2001), doi:10.1109/25.917940
23. Femenias, G.: BER performance of linear STBC from orthogonal designs over MIMO correlated nakagami-m fading channels. IEEE Transactions on Vehicular Technology 53(2), 307–317 (2004), doi:10.1109/TVT.2004.823475
24. Caban, S., Mehlführer, C., Mayer, L.W., Rupp, M.: 2x2 MIMO at variable antenna distances. In: Proc. of VTC 2008 Spring, Singapore (2008), doi:10.1109/VETECS.2008.276
25. Caban, S., Rupp, M.: Impact of transmit antenna spacing on 2x1 Alamouti radio transmission. Electronics Letters 43(4), 198–199 (2007), doi:10.1049/el:20073153

26. Hunukumbure, R., Beach, M.: Outdoor MIMO measurements for UTRA applications. In: Proc. of EURO-COST 2002 (2002), http://hdl.handle.net/1983/887
27. Trautwein, U., Schneider, C., Thomä, R.: Measurement-based performance evaluation of advanced MIMO transceiver designs. EURASIP Journal on Applied Signal Processing 2005(11), 1712–1724 (2005), doi:10.1155/ASP.2005.1712
28. Thomas, T.A., Desai, V., Kepler, J.F.: Experimental MIMO comparisons of a 4-element uniform linear array to an array of two cross polarized antennas at 3.5 GHz. In: Proc. of VTC 2009 Fall (2009)
29. Jungnickel, V., Jaeckel, S., Thiele, L., Krueger, U., Brylka, A., von Helmolt, C.: Capacity measurements in a multicell MIMO system. In: IEEE Global Telecommunications Conference, pp. 1–6 (2006), doi:10.1109/GLOCOM. 2006.645
30. (C) (2009), Microsoft Corporation (2009), http://www.bing.de
31. Mehlführer, C.: Measurement-based performance evaluation of WiMAX and HSDPA. Ph.D. thesis; Vienna University of Technology (2009), http://www.nt.tuwien.ac.at/fileadmin/data/testbed/diss-mc.pdf
32. Caban, S., Mehlführer, C., Langwieser, R., Scholtz, A.L., Rupp, M.: Vienna MIMO Testbed. EURASIP Journal on Applied Signal Processing, Article ID 54868 (2006), doi:10.1155/ASP/2006/54868
33. Mehlführer, C., Caban, S., Rupp, M.: Experimental evaluation of adaptive modulation and coding in MIMO WiMAX with limited feedback. EURASIP Journal on Advances in Signal Processing, Article ID 837102 (2008), http://publik.tuwien.ac.at/files/pub-et_13762.pdf, doi:10.1155/2008/837102
34. KATHREIN-Werke KG Antenna No. 800 10629 (2010), http://www.nt.tuwien.ac.at/fileadmin/data/testbed/kat-ant.pdf
35. Kakoyiannis, C., Troubouki, S., Constantinou, P.: Design and implementation of printed multi-element antennas on wireless sensor nodes. In: Proc. of ISWPC 2008, pp. 224–228 (2008), doi:10.1109/ISWPC.2008.4556202.36
36. Mehlführer, C., Caban, S., Wrulich, M., Rupp, M.: Joint throughput optimized CQI and precoding weight calculation for MIMO HSDPA. In: Conference Record of the Fourtysecond Asilomar Conference on Signals, Systems and Computers. Pacific Grove, CA, USA (2008), http://publik.tuwien.ac.at/files/PubDat_167015.pdf
37. Mehlführer, C., Rupp, M.: Novel tap-wise LMMSE channel estimation for MIMO W-CDMA. In: Proc. 51st IEEE Global Telecommunications Conference 2008 (GLOBECOM 2008), New Orleans, LA, USA (2008), http://publik.tuwien.ac.at/files/PubDat_169129.pdf, doi:10.1109/GLOCOM.2008.ECP.829
38. Fisher, R.: The Design of Experiments. Wiley, New York (1935)
39. Cox, D.: Planning of Experiments. John Wiley & Sons, Chichester (1958)
40. Efron, B., Hinkley, D.V.: An Introduction to The Bootstrap, 1st edn. CRC Monographs on Statistics & Applied Probability, vol. 57. Chapman & Hall, Boca Raton (1994), ISBN 0412042312